A Longitudinal Study of Preparatory Handwriting:

Developing Efficiency in Motor Control

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General Introduction

What is wrong with my child's handwriting?

"Such a question from a concerned parent inevitably makes the researcher squirm. There is no simple answer to why a particular child displays difficulties with handwriting. The etiology is heterogeneous and it would be a bold scientist who suggested a singular cause for all writing dysfunctions."

(Taken from John Wann and Maha Kardirkamanathan, 1991, Computer Diagnosis of Writing Difficulties. In: J. Wann, A.M. Wing & N. Søvik, Eds., Development of Graphic Skills: Research, Perspectives and Educational Implications, p. 225, London: Academic Press)

In 1993 Weil and Cunningham signaled a lack of empirical research on biomechanical aspects of handwriting development and stated that educators and pediatric therapists based their clinical interventions on outdated information. Since then we have gained many new insights into cognitive and motor skills that are involved in handwriting. Nevertheless, the question still remains how to exploit this knowledge to underpin sound, substantiated diagnostic and treatment decision-making processes that are aimed at improving the legibility and speed, i.e. the efficiency of children's handwriting performance, of which the foundation is being formed during the first three years of primary school. The present thesis addresses this challenging question.

Aim

The general aim of this thesis is to study the development of efficiency in motor control in the first three years of primary school. We focus on an educationally highly relevant skill, viz. preparatory handwriting. Eventually, efficiently produced handwriting entails the capacity to coordinate a variety of motor and literacy skills that form the building blocks of handwriting. In order to better understand how these underlying processes unfold in time, and interact during a critical time period in primary school when cursive handwriting is being acquired, we analyzed movement kinematics, stimulus-response coupling and time-dependent self-similarity using a controlled preparatory handwriting-like loop-writing task (resembling the letter *e*), in a longitudinal study. In addition we collected handwriting and literacy performance measures of our participating children in order to try and formulate implications of our analyses for everyday practical assessment and treatment decisions in educational settings.

Background

Earlier efforts to understand deterministic processes that lead to the skill of handwriting originate from four types of research, viz. educational surveys, developmental research, cognitive analyses and motoric studies, each type of science having its advantages and limitations.

Educational surveys

Over the years several models, as described in educational journals, have been proposed to define the processes that are involved in (hand)writing. In 1981 Flower and Hayes posed a model in which three, recursive cognitive processes were thought to interact within a hierarchical structure: planning, translating and reviewing. This model emphasizes cognitive processes representing what needs to be written, monitoring what is being written, and reconsidering what has been written. The emphasis on cognition was accepted as a new focus on the processes of thinking, learning and composing. Since Flower and Hayes' model was solely based on an analysis of adults' handwriting products, the processes involved in learning to produce handwriting or mastering the spelling rules, was not addressed by this model. This deficiency was recognized by Juel, Griffith and Gough (1986) who, in turn, introduced the so-called 'simple view of writing' model, which consists of two basic factors: spelling and ideation. Both factors are considered to account for the development of handwriting in young children. Juel, Griffith and Gough (1986) and Juel (1988) showed in their longitudinal studies that, among others, phonemic awareness and spelling-sound knowledge were important factors for learning to decode alphabetical language which influence the development of handwriting performance and composing skills of first grade primary school children.

In 1985, Berninger started an interdisciplinary, strategic educational research program. The first study explored the relationships between neurodevelopment, language functions and academic skills in children with school 'problems' (Berninger & Coldwell, 1985). According to their view the empirical relationship between neurodevelopmental and educational findings needs to be established first before assessment or diagnosis of handwriting problems test scores can be used. Even though their research did not confirm the close relationship between neurodevelopmental and educational assessment scores, the message was taken: if only for reasons of hypothesis generation, the systematic use of neurodevelopmental measures was since then advocated for school-performance assessment purposes.

In 1992 Berninger and Hart examined developmental dissociations, focusing on functional brain organization in developing children with brain damage and un-referred children without brain damage. They investigated the disparities between the cognitive and motor system in terms of fine motor, orthographic, oral, reading and writing functions. For the cognitive and motor system they concluded that sensorimotor development was not indispensable for overall intellectual development, indicating that developmental dissociations do not develop concurrently. For fine motor and literacy skills they provided findings that with respect to developmental and educational competence, children's skills show large inter-individual variability, that develop independently of one another.

The role of handwriting in spelling and composing was further investigated against the backdrop of four functional language systems. Language as a system develops from receptive-aural speech perception and expressive-oral speech production to a next level where children learn to read and write by using the eye and hand. They learn to produce a visible trace, using the alphabetical letter system. Language by hand is thus an integration of letter sounds (phonological coding), graphemes (orthographic coding), and the output or graphomotor codes (Berninger et al., 2006). Consequently, they proposed that handwriting cannot be seen as a pure motor act, but is highly dependent on the capacity to recall letter shapes. Memory and spelling therefore contribute more to handwriting than motor skill; furthermore, memory processes and spelling capacity are part of the route to automaticity in handwriting production. All levels of the language system are thus interrelated (Berninger, 2000; Medwell & Wray, 2007).

In 2002, Berninger's research group expanded the 'simple view of writing' into three components: (i) transcription, which entails handwriting in the form of letter production and (ii) spelling, being word production, taken together as 'low-level' developmental skills as opposed to: (iii) executive functions such as planning, monitoring, revising and text generation, which includes writing at word, sentence or text level, characterized as 'higher level' skills (Berninger, Yates, Cartwright, Rutberg, Remy, & Abbot, 2002).

From 2006 on, the role of motor processes in dyslexia was further evaluated. The finger-succession task (Berninger & Rutberg, 1992) was found to be a reliable indicator of a graphomotor factor affecting the orthographic loop in working memory. The finger- succession task requires planning of sequential finger movements and is, contrary to the repetitive finger-opposition task, representative for serial behavior (Richards et al., 2009). The orthographic loop is responsible for the storage of information in working memory and represents how a word is written in terms of eye-hand coordination (Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008). Moreover, they concluded that graphomotor planning was not the only contributor to compositional skill, but automatic letter naming on the one hand and writing and verbal fluency on the other hand could disclose spelling problems and might reflect a general deficit in automaticity.

Finally, more recent neurocognitive and brain-imaging studies (using methods such as PET, MEG and fMRI), especially concerning finger movements, have been incorporated in the interdisciplinary research of the development of literacy skills. Early research in this context by Shibasaki et al. (1993) found a higher increase in blood flow in the supplementary motor areas, sensorimotor cortex and cerebellum for the finger-succession task than for the finger-opposition task (see also Roberts, Disbrow, Roberts, & Rowley, 2000). The relevance of the supplementary motor area is that it is involved in organizing forthcoming movements in complex motor sequences that require precise timing (Abbruzzese, Trompetto, & Schieppati, 1996; Gerloff, Corwell, Chen, Hallett, & Cohen, 1997), the sensorimotor cortex controls movements and codes sensations for touch and kinesthesia while the cerebellum controls timing and coordination of motor output. In an fMRI studies of fifth-grade writers Richards et al. (2009) found that good and poor writers differed on the sequential-finger task. Good and poor writers were defined by using the alphabet task (according to Berninger & Rutberg, 1992: requiring children to retrieve and produce alphabet letters in sequence, thereby integrating orthographic symbols and motor output) and the spelling subtest of the Wechsler Individual Achievement Test. Recently Pontart and her colleagues (2013) have challenged the use of the alphabet task since the test is not so easy to interpret. Graphomotor skills are not the only aspect of handwriting that is addressed by writing an alphabet, the knowledge of phoneme-grapheme correspondence is also tested, and furthermore writing isolated letters is not an every day task. They suggested using the more ecological task of name writing to improve the assessment of handwriting skills. Also using fMRI studies, James and Atwood (2009) and James (2010) demonstrated that "*there is a distinct system in the human brain that is recruited during reading that is also recruited during writing; b) that the reading network develops as a function of handwriting (printing) experience; and c) that handwriting (printing), and not keyboarding, leads to adult-like neural processing in the visual system of the preschool child. These findings suggest that self-generated action, in the form of printing letters by hand, is a crucial component in setting up brain systems for reading acquisition"* (Cited from the abstract: 'The neural correlates of handwriting and its affect on reading acquisition', presented at the Handwriting in the 21st Century Summit, 2012, Washington DC).

In conclusion, findings from the programmatic educational research of Berninger's group suggest non-specific relations between cognitive-educational measures and motor-developmental measures. Letter production (alphabet task, sub-word level of transcription) and spelling (word-level transcription) are well-defined components of handwriting and may influence the development of technical handwriting. The finger-tapping task, gauging sequencing, one of the tests to assess soft neurological signs, is proven to be clinically (finger-succession task) as well as functionally (fMRI, finger tapping) a reliable means to differentiate between children with good and poor handwriting.

Developmental research

This type of research is primarily oriented on the development of handwriting as a visible product and the way handwriting is learned (Feder & Majnemer, 2007; see for an overview Ziviani & Wallen, 2006). Handwriting, defined as the process of transcribing letters into words and words into sentences (Ziviani & Wallen, 2006), is here seen as a motor task that needs to be acquired. In general, developmental progression is observed in both legibility and speed of handwriting (Graham, Berninger, Weintraub, & Schafer, 1998; Hartley, 1991; Ziviani, 1984). Some 10% of the children are left handed, which is not necessarily associated with illegible handwriting (Ziviani & Elkins, 1986). A plethora of test batteries exist for these measures.

In the Netherlands the 'Beknopte Beoordeling voor Kinderhandschriften' or BHK (Hamstra-Bletz, De Bie, & Brinker, 1987) and recently the 'Systematische Opsporing Schrijfproblemen' or SOS-2-NL (Smits-Engelsman, Van Bommel-

Rutgers, & Van Waelvelde, 2013) have been constructed to capture the developmental level of a child's handwriting skill. The development of the quality and speed of handwriting is measured in terms of grade-related legibility and speed scores. Legibility is judged by assessment of letter formation and size, horizontal alignment, and spacing. For handwriting speed the number of letters written within 5 minutes is counted (Hamstra et al., 1987; Smits-Engelsman et al., 2013).

The handwriting skill does not show a spontaneous development; letterforms and words (legibility) to produce a written product have to be taught and trained in school settings and speed follows the growing performance. For each country, local conventions and choices of direction and letterform define the final hand written products. Both legibility and speed show a growing skill capacity over time reflecting development as well as learning.

Cognitive studies

In addition to educational and developmental research in the 1980s and 1990s, handwriting was increasingly applied in motor control studies that emphasized the *interface between language and movement* (e.g. Bogaerts, Meulenbroek, & Thomassen, 1996; Newell & Van Emmerik, 1989). The evolution of new recording techniques such as digitized tablets and the development of theoretical models together with the formation of the International Graphonomic Society (in which researchers from multiple disciplines brought together their fields of interest) facilitated this type of handwriting research. Issues surrounding the cognitive representations governing handwriting production and development were formulated in research of 'motor programmes' (Teulings, Thomassen, & Van Galen, 1986), timing patterns (Van Galen & Teulings, 1983), the individual strokes in letters (Hulstijn & Van Galen, 1983), and of multiple processes in handwriting (Van Galen, Meulenbroek, & Hylkema, 1986). The mixed linear and parallel model of handwriting by Van Galen (1991) is a notable example of a widely cited information-processing model, representing a growing interest in cognitive modeling. The model defines the following processes: 1) activations of intentions, 2) semantic retrieval, 3) syntactical construction, 4) spelling, 5) allograph selection, 6) size control, and 7) muscular adjustment, each process working on a different, i.e. progressively smaller, time scale. Handwriting is thus seen as the end product of several cooperating processing stages, each of which is involved in the preparation and monitoring a different aspect of the task (see also Thomassen & Van Galen, 1992; Van Galen, 2006). This view is indebted to a theory of motor coordination coined by Bernstein as early as 1939 as a multilevel (structural and functional) system of motor control with a complex distribution of tasks (Gurfinkel & Gordo, 1998). Here Bernstein described five brain-related levels comprising the origin of tone, self perception, representations of the body and internal and external space constructs at the level of actions, including for example semantic chains.

The research into language and motor processes provided evidence that handwriting cannot be understood without taking linguistic aspects into account (Greer & Green, 1983; Kandell, Álvarez, & Vallée, 2006; Kandell, Spinella, Tremblay, Guerassimovitch, & Álvares, 2012; Thomassen & Schomaker, 1986; Van Galen, 1991; Wing, Nimmo-Smith, & Eldridge, 1983).

Motor studies

Purely motor studies investigated handwriting at the level of effects of amplitude, direction, duration, curvature, and force constraints on the dynamics of handwriting. The systematic relationships that exist between spatial and temporal movement parameters have been captured in principles such as Isogony, the two-thirds Power Law (Lacquaniti, Terzuelo, & Viviani, 1983), Isochrony (Viviani & Terzuolo, 1982; Viviani & McCollum, 1983), and the speed-accuracy trade off known as Fitts' Law (Fitts, 1954). The isogony principle addresses timing in curvilinear trajectories (i.e., equal angles in equal time) and the two-thirds power law describes the inverse relationship between the instantaneous curvature of planar movements and tangential movement velocity. The isochrony principle (i.e., different amplitudes in constant movement time) and Fitts' Law (i.e., movement time scales logarithmically with amplitude and inversely with target width) describe two different relationships between movement amplitude and duration. For small amplitudes (< 10 mm) paths of different lengths do not require different movement times whereas for larger amplitudes the movement time scales logarithmically to amplitude. Several information-processing models have been proposed to explain the relation between speed and accuracy in target-directed manual aiming, ranging from the importance of feed-forward processes to accuracy in target-directed manual aiming, while the role of practice in optimization of speed, accuracy and energy expenditure is also considered (see Elliot, Helsen, & Chua, 2001, for a review; Elliot, Hansen, Mendoza, & Tremblay, 2004).

The way trajectories of the pen tip evolve on the writing surface is also used to describe the influence of biomechanics on handwriting production. The fingers, thumb, wrist, elbow, arm and shoulder joints, taken together as the effector system used for handwriting, can be modeled as a redundant system with many degrees of freedom, which need to be controlled in order to write legibly (Latash, Danion, Scholz, Zatsiorsky, & Schöner, 2003). Theoretical suggestions and empirical results underline that the acquisition of motor skills entails managing the redundancy of the movement system, i.e., by compressing a high- dimensional system composed of many components into a low-dimensional system with only few macroscopic or collective variables that need to be controlled (Athènes, Sallagoïty, Zanone, & Albaret, 2004; Bullock, Grossberg, & Mannes, 1993; Riley, Mitra, Stoffregen, & Turvey, 1997). At the biomechanical level velocity and acceleration patterns are informative for handwriting fluency (Meulenbroek & Van Galen, 1988; Van Doorn & Keuss, 1991), while analysis of the number of inversions in velocity profiles reveals the noisiness in handwriting movements, potentially neuromotor tremor (Van Galen, Poitiers, Smits-Engelsman, & Schomaker, 1993). Accuracy in graphic control is also related to workspace, as children proved more accurate in their ipsilateral space than in their contralateral space (Smits-Engelsman, Swinnen, & Duysens, 2004). Focusing on the kinematic aspects of handwriting, the maturation of the coordination of proximal and distal articulations clearly affects development of handwriting. Issuing orders to increase speed and write between lines is beneficial for children at the beginning of their learning process (Chartrel & Vinter, 2008; Meulenbroek & Van Galen, 1988; Mojet, 1991).

In sum, since the 1980s many motor studies have explored efficiency principles in handwriting production, all of which contributed to our understanding of the underlying processes of handwriting and handwriting development.

Question

The main research question which is addressed in this thesis concerns the interplay between motoric, cognitive, and language processes in handwriting when primary school children, through extended practice, acquire this perceptuomotor skill in the first three years of handwriting instruction. The specific questions of each of the empirical studies that we report are specified below. First, we summarize the general methodology that we applied in our longitudinal preparatory handwriting study.

Methodology

Participants

In this thesis we report the results of a three-year longitudinal study in which

we followed the handwriting development of a group of 34 children from two mainstream elementary Dutch schools from Grade 1 to Grade 3. At the start of the study they resided in two different first grade groups of two allied schools. They were tested each year around March. At the first measurement in Grade 1 their mean age (in years and months) was 7;0. Four girls and two boys were left-handed. In the course of the study, two right-handed children were excluded from this study due to a change of schools. One of the children had to repeat Grade 1, whilst the other child went to a school for children with special needs.

All the parents of the children gave their informed consent. Experimental procedures followed the APA guidelines for the ethical treatment of human participants. The ethics committee of the Faculty of Social Sciences of the Radboud University approved the study and since it was a behavioural study, approval of a medical ethics committee was not considered necessary.

Tasks and Procedures

We used a repetitive loop-writing task to probe the motoric and cognitive development at a kinematic level. Loop writing is a specific non-linguistic handwriting-like task, which resembles the letter *e*. In essence, the task can be modeled as the continuous production of circles or ellipses superimposed upon a linear left-to-right progression movement (Hollerbach, 1981). Compared to other cursive handwriting tasks in which the shape of letters often consists of different combinations of up and down strokes, loop writing can be regarded as a relatively simple repetitive motor task (Meulenbroek, Thomassen, van Lieshout, & Swinnen, 1998).

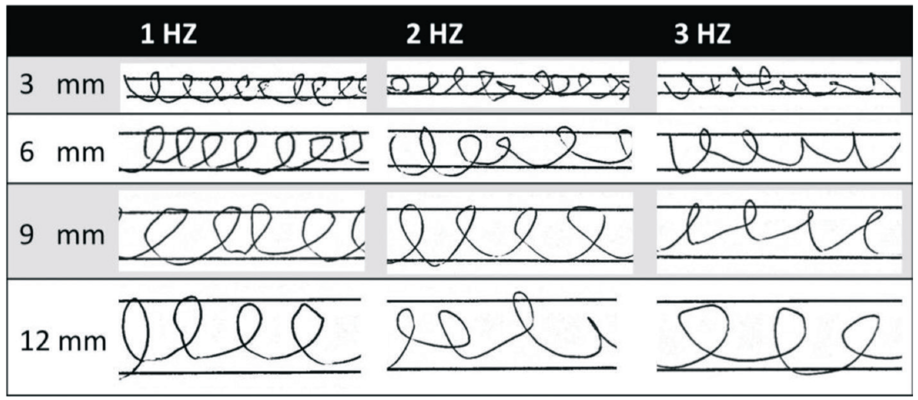

Figure 1. *Sample of handwriting products generated in the experimental loop-writing task by an 8- year-old right-handed male pupil.*

The loop-writing task was executed on a preprinted sheet of paper attached to a digitizer tablet. The loop-pattern height was 3, 6, 9 or 12 mm and the task was paced by an acoustic signal of 1, 2, or 3 Hz (see Fig. 1) of which the intensity changed sinusoidally across a clearly audible range. This paced loop-writing task was used in all studies. An experimental session consisted of twelve blocks of six repetitions of each amplitude-frequency combination, presented at random. Frequency-amplitude combinations did not differ within a block. The result was a total of 72 trials per session within a time span of 45 minutes. The sampled handwriting movements were analyzed off-line with Mat lab V 7.0.0.19920(R14). Our choice for an acoustical paced and spatially restricted repetitive loop writing task, was rooted in the idea that the higher pacing frequencies challenged the children's amplitude production accuracy, which we assumed to increase the sensitivity of our assessment of the fine motor coordination required for producing handwriting.

The three empirical studies that we report are based on analyses of digitized handwriting movements obtained by using the handwriting-like loop-writing task, resembling the letter *e* (Chapter 2, 3 and 4). For the fourth study standard reading, spelling and handwriting performance indices complemented the loop writing performance (Chapter 5). In the fifth study, the measurements of the fourth study were used for a double case study of two children, describing the variability of development on an individual level against the backdrop of the general development of their group (Chapter 6).

The participating children were tested individually for the loop-writing task whereas their teachers assessed the handwriting in a group session, which was later judged by the physical therapist. The teachers assessed the language measures using test prescribed by the central institute of test development (CITO) and marked the outcome measures in the school following system, from which the measures were derived by the tester.

Data analysis

To quantify the motor, cognitive and educational aspects of the children's handwriting skills, we analyzed a variety of behavioral measures. To assess motor performance, kinematic aspects of the loop writing were analyzed with regard to the spatial and temporal error measures, how local parameter errors changed from one movement to the next and stimulus-response measures. We also scrutinize the underlying flexibility of performance by determining the self-similarity of the produced time series. To quantify the cognitive and developmental capabilities that are involved in handwriting the quality and speed of the children's handwriting was assessed, using a standardized handwriting test. Finally, to assess educational measures we determined reading and spelling indices.

Motoric measures

The cyclical nature of the loop-writing task affords the use of several kinematic performance measures to follow the children in their development over the years: the Absolute Error of Amplitude (AEAmp) and Frequency (AEFreq) and the Standard Deviation of the Relative Phase (SDRph) between the imposed acoustic pacing signal and the vertical pen displacements. As elaborated on in the respective chapters, the error measures formed the basis of detailed analyses of the efficiency with which the children changed their movement-parameter errors from cycle to cycle both within and between the trials. In this study, the SDRph reflects the degree to which the auditory input and the motor output are synchronized.

Another advantage of the cyclical nature of the loop-writing task is that it can be used to measure the structure of movement variability by applying autocorrelation time-series analyses and by calculating the Hurst exponent (Ihlen, 2012; Jebb, Tay, & Huang, 2015). Since variability is a natural feature of human movement and mature motor skills are associated with an optimal amount of movement variability, this feature is indicative of a flexible and rich movement repertoire (Adolph, Cole, & Vereijken, 2014; Newell & Vaillancourt, 2001). At present, several methods are available for estimating movement variability. For one of the studies in this thesis, we chose long- and short-term autocorrelations and the Hurst exponent of the vertical pen-tip displacement as a measure of time-dependent self-similarity in repetitive movement tasks. Time-dependent self-similarity is indicative for the influence of past behavior on ongoing and future behavior. In this context, a weaker Hurst exponent also reflects less time-dependent self-similarity, while a Hurst exponent larger than 0.5 provides assurance that the time-series under consideration are not just random noise (Ihlen, 2012).

Handwriting Performance Measures

For cognitive measures we turned to developmental performance measures as obtained by means of standardized handwriting tests that were not derived from digitized handwriting movements. We here label these measures performance measures because they depend on the assessment of the written products from which we presume to reflect cognitive capabilities with respect to language and movement planning processes involved in handwriting.

The handwriting performance measures were collected with the Concise Assessment Scale for Children's Handwriting (acronym: BHK, 'Beknopte Beoordelingsmethode voor Kinderhandschriften'; Hamstra-Bletz, De Bie, & Den Brinker, 1987). The BHK assesses quality and speed of handwriting in relation to norm scores. A comprehensive description of the psychometric properties and test structure can be found in chapter 5. The quality score is norm-referenced for children in Grade 2 and 3 and the scoring for speed uses the norm- scores for children in Grade 1-6. For this study over three years of development, the BHK-test is performed as group test in the classroom setting. The test is sensitive enough for measuring changes over development (Hamstra-Bletz & Blöte, 1990, 1993; Overvelde & Hulstijn, 2011). The child's total score on all 13 items is used to determine whether the child either has a normal, i.e. not-dysgraphic, score (0-21), an ambiguous score (22-28) or a dysgraphic score (29 or higher). Since the BHK-test gives no norm-references for children in Grade 1, two experienced teachers were asked to apply one of the three categories, by analyzing the quality of the handwriting using their knowledge of developing handwriting in this grade. On two children there was no agreement, a third teachers' opinion was decisive. Following the yearly testing in Grades 2 and 3, the quality of the handwriting of each child was assessed by two experienced pediatric physical therapists. When no agreement was reached, a third experienced pediatric physical therapist was consulted whose opinion was decisive. Handwriting speed was measured by counting the number of letters produced in exactly five minutes and translated in deciles scores related to the child's grade. The deciles 1 and 2 reflect a slow writer, the deciles 3 to 8 a typical writer and the deciles 9 and 10 a fast writer, in this study defined as slow writers, typical writers and fast writers. (BHK: Hamstra-Bletz et al., 1987).

For the cognitive capabilities of the children in the loop-writing task, we focused on how local amplitude and frequency errors changed from one movement to the next. Exploitation of biomechanics, when the children respected the inverse relationship between movement amplitude and frequency, was distinguished from deliberate, cognitive control when the children succeeded in overriding the inverse relationship between movement amplitude and frequency. This approach assumes that error correction in cyclical movement tasks also demands cognitive processing.

Educational Measures

In our study, two language-skill measures were drawn from the standardized child educational monitoring system (LOVS or 'Leerling- en Onderwijs-Volg-

Systeem'), which is a systematical follow-up system, used by schools to measure the progression of students twice a year. For the language measure of technical reading we used the AVI ('Analyse van Individualiseringsvormen', Visser et al., 1998), measuring how fast children can read under speed and accuracy constraints that are appropriate for their age. For the language measure "spelling" we used the Spelling Test (CITO, 2006) formerly the SVS ('Schaal Vordering in Spellingsvaardigheid', 'Cito-Spellingstoetsen'; van den Bosch et al. 1997), which gauges spelling in writing words to dictation.

The test scores of the LOVS reflect, among others, the impact of the education at the level of the individual student. The tests are developed by the CITO (Central Institute for Test Development), and comply with the criteria for quality of COTAN (Dutch Committee on Tests and Testing). We used the test scores from the second evaluation period, which takes place around January/February. For the individual child the LOVS system calculates, among other measures, a *'didactical age'* expressed as the sum of all educational months, with a total of 10 months for each school year, a *'didactical age equivalent'* for a specific test score, expressed in educational months, and a *Learning Output Percentage* (LOP, 'leerrendement') as a relative norm score. A LOP of a 100% means that a pupil meets the learning demands of his/her grade, a higher percentage reflects that the pupil is a fast learner; a lower percentage reflects he/she is a slow learner. Finally the LOVS has an A to E score in relation to national scoring levels (followed by the learning output percentage in brackets, adapted by the LOVS to grade and national mean): A: 25% of highest scores (LOP: >116); B and C: 25% just above and 25% just below the national mean level (LOP: 84-116); D: 15% between dispersion around mean and lowest score (LOP: 83-67) and E: 10% of lowest scores (LOP: <66). Children attaining an A, B or C score fall within the normal dispersion of educational scores, children reaching D and E scores are eligible for extra care.

Results: Outline of the thesis

The current chapter describes the theoretical and empirical background of our study, explains the loop-writing task and the methodological perspectives as regards our choices in motoric, literacy and educational performance measures.

In this first study, we explored how children in the first year of handwriting development learn to simultaneously control multiple spatio-temporal goals. We investigated how biomechanical and intentional control principles compete in preparatory writers. Theoretical groundings in this study are based on observations that when participants are simultaneously confronted with spatial and temporal constraints in an ellipse-drawing task, they will either exploit the intrinsic amplitude-frequency relationships or activate less natural control regimes to prioritize their movement goals (Bosga, Meulenbroek, & Rosenbaum, 2005). Also, studies (Rosenbaum, Slotta, Vaughan, & Plamondon, 1991; Vaughan, Rosenbaum, Diedrich, & Moore, 1996) have shown that movements with large amplitudes tend to be performed at low frequencies and movements with small-amplitude usually operate at higher frequencies, which is reflected in respectively shoulder-elbow and wrist and finger rotation. Furthermore, efficient handwriting implies the capacity to control movement parameters such as amplitude, distance and speed (Van Galen, 1991). And finally, the learning phases as proposed by Fitts and Posner (1967) suggest cognitive learning strategies in the initial stage of learning a motor skill followed by rule-based learning and automatization.

We presumed that if the child perceived the current movement cycle to be too small or large or too fast or slow, the child would be inclined to correct this mismatch in the next movement cycle. If the correction is realized by respecting the inverse relationship between amplitude and frequency we interpreted the correction to be the result of a strategy of exploiting the biomechanics of the movement system. However, if the correction is realized by disregarding the inverse biomechanical relationship we presumed that the child deliberately overruled this biomechanical relationship and was taken by us to be indicative of overriding cognitive control. This would fit in the first learning phase as proposed by Fitts and Posner (1967): at this stage in their development we presumed that the children would use a more cognitive strategy to reach multiple movement goals.

Chapter 3 builds on the study of preparatory writers described in chapter 2. In this study we examined the movement efficiency of children in Grades 1, 2 and 3 of primary school by scrutinizing their movement amplitudes and frequencies as they settled into a loop-writing task in which both parameters were prescribed. Since several time scales collectively reflect change in performance and control, we were interested in the possibilities to differentiate in task adaptation as a more local aspect of learning and development. We expected the children to be able to settle into the task quickly and furthermore show development of task adaptation over the years. Given the fact that amplitude containment is important for children, as is emphasized in school settings, we also investigated differences between adaptation to amplitude and frequency instructions. As preparatory writers the children in Grade 1 were able to exploit the inverse relationship between amplitude and frequency as follows from Fitts' Law (1954).

In this study we therefore expected typically developing children between 7 and 9 years of age to improve their ability to contain movement errors, but most of all, to demonstrate more efficient error correction.

Chapter 4 takes the end-point variability measurements of the first two studies a step further towards the underlying intrinsic variability of the neuromotor system. Instead of focusing on the cycle-to-cycle movement error correction strategies of the children, we were interested in the short- and long-term intrinsic variability. We define intrinsic variability as a time-varying exploration of many solutions to a movement task and take it to reflect the capability of children to allow the best solution to solve a motor task to emerge to attain stable performance. Time-series analyses, in this case autocorrelation measures, have recently been proposed to quantify changes in behavioral flexibility. Autocorrelations assessed with varying time lags, by definition, capture behavioral regularities on a spectrum: weaker autocorrelations reflect less time-dependent self-similarity in the movement patterns, which is taken to indicate behavioral flexibility. Weaker short-term autocorrelations of cyclically performed movements' mean that at a particular moment in time, the ongoing behavior is less influenced by past behavior and past behavior and ongoing behavior is less likely to influence future behavior. In contrast, stronger autocorrelations reflect greater time-dependent self-similarity in the movement patterns, which is taken to reflect behavioral rigidity, i.e., earlier behavior is more likely to determine present and future behavior.

We expected the children to become, over the years, more flexible in adapting their performance to environmental and task constraints.

The theme of the exploratory study in chapter 5, which combines cognitive, educational, and motor measures, is the development of relationships of language (constricted to reading and spelling capacity in school settings) and handwriting as reflected by performance and process measures. The development of handwriting skills in the first three grades of primary school strongly depends on the gradual automatization of "lower level" (fine) motor, spelling and reading skills. This chapter considers the extent to which the various literacy skills assessed separately by means of school performance tests, contribute to the development of handwriting speed observed in this age group. The changes in performances between Grades 1 and 2 and Grades 2 and 3 were also considered. A product measure (The BHK: Hamstra-Bletz, 1987) was used to define handwriting speed and quality. Reading and spelling performance measures were extracted from the school-educational system and motor process measures from the loop-writing task were used to define error in performance without the burden of language capacities.

Following the general trend form the educational literature we also expected for this group of children a strong relationship between handwriting performance and literacy skills at the start of handwriting education, which would disappear over the three years of development. We also expected the amplitude errors to be related to handwriting performance.

To bridge the gap between our studies at the group level to diagnostic challenges at the individual level in an educational setting, we described in chapter 6 the individual development of two separate children from our longitudinal study who, halfway into our study, happened to be diagnosed with lasting dysgraphic handwriting development on the basis of diverse assessments. In this explorative and hypothesis forming study, we described the individual development of the spelling, reading and handwriting performance of these two children and used new insights in interdisciplinary counseling to reflect on the usefulness of combined assessment scores for diagnostic decisions within a school context.

Chapter 7 contains a general discussion of the studies reported in this thesis. Here we also reflect on implications of our research for pediatric physical therapists when assessing children with atypical handwriting development and give some considerations to treatment decisions for atypical handwriting development in school settings. Finally, some thoughts are given to the possible use of regularity statistics in future handwriting research.

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Chapter 2

Intentional Control and Biomechanical Exploitation in Preparatory Handwriting

CHAPTER 2

Intentional Control and Biomechanical Exploitation in Preparatory Handwriting

2

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Abstract

In this study it was investigated how primary school children perform a graphomotor task, which required them to simultaneously achieve multiple movement goals. Thirty-four 1st grade primary school children were asked to produce with an electronic ink pen loop patterns varying in height (3, 6, 9 and 12 mm) on preprinted sheets of paper attached to a digitizer tablet. The task was paced by means of an acoustic signal of either 1, 2 or 3 Hz. The children were instructed to attain both the imposed amplitude and frequency. By focusing on how local parameter errors changed from one movement to the next, exploitation of biomechanics when the children respected the inverse relationship between movement amplitude and frequency was distinguished from deliberate, cognitive control when the children succeeded in overriding the inverse relationship between movement amplitude and frequency. The results show that children, like adults, exploit biomechanics to a considerable extent. Coupling strength between the acoustic pacing signal and the pen-tip movements increased with age whereas the temporal errors decreased. The study shows that preparatory writers can pursue multiple movement goals simultaneously at lower speeds but at higher speeds their capacity to do so is reduced.

Introduction

First graders learn and develop handwriting skills against a backdrop of instructions and exercises including fine motor control with a pen (graphomotor), a correct way of using a specific script, particularly spelling (orthographic), and naming skills (phonological). Research has shown that adaptation, learning, and development, each on a different time scale improve the behavioral performance of handwriting skills in children even though mastering this skill does not necessarily evolve in a linear fashion (Hamstra-Bletz & Blote, 1990; Meulenbroek & Van Galen, 1986; Rueckriegel et al., 2008). Because efficient handwriting presupposes skills at multiple levels of the psychomotor hierarchy (Van Galen, 1991), it implies the capacity to simultaneously satisfy multiple task goals related to the relative timing of sub movements, amplitude, distance between letters and words, and direction and speed. How children learn to control multiple movement goals simultaneously has seldom been studied and we therefore focus on this matter here by exploiting a loop-writing task that we recently developed to study multiple parameter control (Bosga, Meulenbroek, & Rosenbaum, 2005).

As regards the growing ability to control multiple movement parameters, the views of Fitts and Posner (1967) on motor learning are relevant. Fitts and Posner proposed that skill acquisition progresses in three learning phases. In the *cognitive phase,* the primary problem to be solved concerns "what is to be done". The learner needs considerable cognitive activity to discover appropriate strategies to solve the movement puzzle he or she is confronted with. In the *associative phase* the learner knows what to do but tries to find the most efficient way of doing the task. Over a longer period of time subtle changes are being made in this phase and movements become more consistent. In the *autonomous phase,* finally, the learner is able to carry out the skill with little conscious effort and the task can be performed with hardly any interference from other simultaneous activities (Schmidt & Lee, 1999; Schmidt & Wrisberg, 2004).

With respect to multiple parameter control in movement production it has further been observed that large-amplitude arm movements tend to be performed at low frequencies by means of shoulder and elbow rotations, whereas small-amplitude arm movements tend to be performed at higher frequencies by means of wrist and finger rotations (Rosenbaum, Slotta, Vaughan, & Plamondon, 1991; Vaughan, Rosenbaum, Diedrich, & Moore, 1996). Asking participants to depart from these movement patterns (e.g., to produce fast shoulder movements or slow wrist rotations) requires them to refrain from relying on intrinsic amplitude-frequency relationships and instead to activate less natural, possibly more attention-demanding control regimes (cf. Bosga et al., 2005; Zelaznik, Spencer, & Ivry, 2002).

In the present experiment we focused on local amplitude and frequency errors and parameter changes from one movement to the next during loop writing with different imposed amplitudes and frequencies. How would preparatory writers minimize their movement errors and how can they achieve such control? The purpose of the underlying study was twofold. First, by contrasting younger and older first graders, we set out to determine the relative importance of age and learning in minimizing movement errors in our task. Second, we aimed to quantify how preparatory writers perform a specific version of the seemingly simple graphomotor task of loop writing in which we asked them to simultaneously achieve multiple spatio-temporal goals.

Our predictions are illustrated in Fig. 1. The center of Fig. 1 shows a hypothetical goal combination amplitude-frequency combination. Around the centrally located goal-parameter are eight categories of possible performance errors. Single-parameter errors (A^+F^0, A^0F^+, A^-F^0, and A^0F^-) are shown on the dashed lines and correspond with either the amplitude or frequency of the movement being identical to the goal-parameter value. Double-parameter errors (A^+F^+, A^-F^+, A^-F^- and A^+F^-, i.e., errors in both amplitude and frequency) are depicted in the four quadrants and correspond with both amplitude and frequency simultaneously being off-target. Fig. 1 also shows a hypothetical series of attempts to reduce the errors from one movement to the next in response to performance error. In the depicted case, the initial error is an amplitude that is too large (A^+) and a frequency that is too low (F^-). The error-reduction process is represented by a sequence of four arrows. Let movement *i* be a single loop of particular amplitude and frequency. Various outcomes are possible for movement *i*+1. One possibility is that both the amplitude and frequency of movement *i*+1 are identical to those of movement i. By contrast, one or both of the parameters of movement *i* +1 differ from those of movement i, in which case one of three outcomes is possible. (1) Either the amplitude or the frequency of movement *i* + 1 differs from that of movement i. In both cases, we speak of a *single-parameter change.* (2) The amplitude of movement *i*+ 1 increases and the frequency of movement *i*+1 decreases, or the amplitude of movement *i*+1 decreases and the frequency of movement *i*+1 increases. In both cases two parameters change, but the participant may have intentionally changed only one parameter and the other parameter may have changed passively on the basis of the natural relationship between amplitude and frequency. We call such changes *quasi-double-parameter changes.* (3)

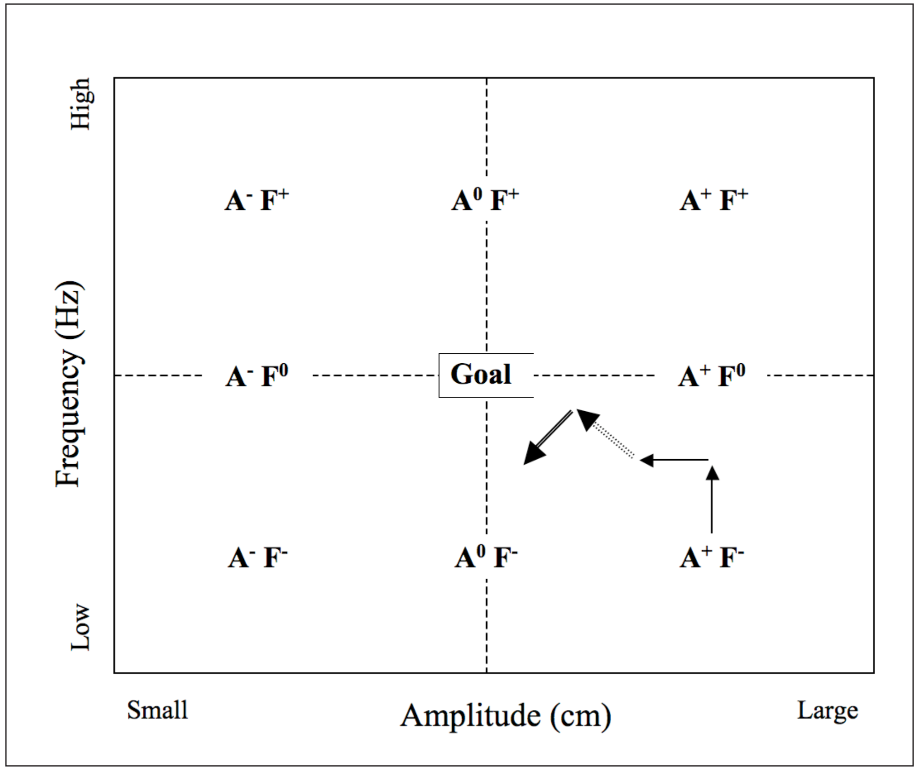

Figure 1. *Possible changes in performance in successive trials. Eight categories of possible performance errors are shown with respect to the goal amplitude-frequency combination, shown at the center. Single-parameter errors (A^+F°, $A^\circ F^+$, A^-F°, and $A^\circ F^-$) correspond to the positive and negative directions of the dashed x (Amplitude) and y (frequency) axes. Double- parameter errors (A^+F^+, A^-F^+, A F, and A^+F^-) correspond to the four possible combinations of positive and negative directions of amplitude and frequency. The sequence of arrows towards the goal-parameter combination depicts a hypothetical series of transitions in amplitude - frequency space, beginning with an amplitude that is too large (A^+) and a frequency that is too low (F") relative to the goal. The first solid arrow pointing upward represents a single- parameter change in the frequency domain, the second solid arrow pointing leftward represents a single-parameter change in the amplitude domain, the third double -dashed arrow indicates a quasi-double-parameter change and the fourth double-solid arrow represents a double-parameter change (see text).*

Both the amplitude and frequency of movement *i*+1 increase or decrease. Here we speak of intentionally driven *double-parameter changes* because the combined changes defy the natural, biomechanical relationship between the two parameters (i.e., the inverse relation between frequency and amplitude; cf. Bosga et al., 2005).

First of all, we assumed that children would, from one movement to the next, try to maintain movement errors to a minimum, i.e., if in a certain movement cycle the amplitude was too large or too small, the child was expected to reduce such error in the next movement. Similarly, if in a movement cycle the movement frequency was off-target, the child was expected to correct that timing error in the subsequent movement. Even though younger and older first graders have received the same amount of instructions and exercise time, we assumed that less mature first graders would produce larger movement errors than more mature first graders.

Second, if children respected the inverse relationship between movement amplitude and frequency while reducing their amplitude and frequency errors from one movement to the next, this was distinguished as a motor control regime reflecting exploitation of biomechanics. If, however, children attempted to override the inverse relationship between movement amplitude and frequency when reducing their movement errors this was distinguished as a motor control regime reflecting deliberate, cognitive control. In line with the proposed learning phases by Fitts and Posner (1967), we therefore expected that when preparatory writers are simultaneously confronted with spatial and temporal constraints in our loop-writing task, they would predominantly activate cognitive control regimes to prioritize their movement goals. We also expected to demonstrate that, whereas at low movement speeds preparatory writers can pursue multiple movement goals simultaneously, at higher speeds their capacity to satisfy multiple task goals would be reduced.

Method

Participants and procedure

Fifteen female and nineteen male first grade preparatory writers, recruited from two primary schools were asked to participate in this study. All children were promoted pupils. Their mean age - in years and months - was 7:0 (female 7:1 and male 7:0). All children had normal hearing and normal or corrected-to-normal vision. None had motor problems. All parents of the children gave their informed consent. Experimental procedures followed the APA guidelines for the ethical treatment of human participants. The following procedure was used to determine whether a child was allocated to the younger or older first grade group. In the Netherlands, the school curriculum starts in September and ends in July. A child must be six years of age before the first of November of that year to be admitted to the first grade. The first grade can therefore contain children who just turned six and children who are nearly seven at the start of the curriculum. The experiment took place in the month March of the school year. At that point, the youngest group consisted of those who were 6 years of age (age in years and months - mean: 6.10, *SD* 3 months), the oldest group harbored those of 7 years of age (age in years and months - mean: 7.5, *SD* 1 months). The younger group contained 13 boys and 10 girls and the older group 6 boys and 5 girls. Before the experiment started, the participants were verbally instructed and allowed to perform the task a few times to get comfortable with experimental procedures and task requirements. The children were required to write loop patterns with an electronic ink pen (Intuos3) on preprinted sheets of paper attached to a digitizer tablet (WACOM A4 Over-size tablet). The loop pattern's height was either 3, 6, 9, or 12 mm and the task was paced by an acoustic signal of either 1, 2, or 3 Hz. The pacing signal's intensity changed sinusoidally across a clearly audible range (approximately 60-70 dB; tone pitch 330 Hz). Each of the 12 preprinted trial sheets, with each block consisting of six repetitions of the twelve amplitude-frequency combinations, was presented at random (see Fig. 2). Frequency-amplitude combinations did not vary within blocks. Each child performed 72 trials of 18 loops per trial, leading to a theoretical total of 44,000 loops for the experiment. On-line recordings of X, *Y*, and Z (axial pen pressure) were sampled at 200 Hz.

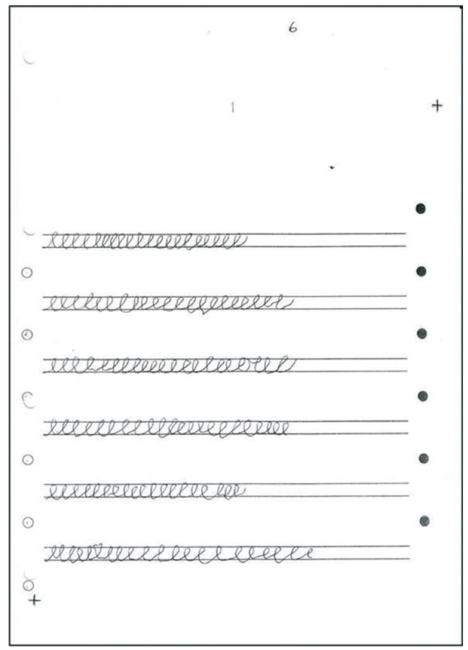

Figure 2. *Example of a block of six writing traces of child nr. 3 under combined amplitude (6 mm) - frequency (1 Hz) constraint.*

Data analysis

All trials were visually inspected and 224 trials were rejected either due to the inability of the child to perform the prescribed task or due to corrupted data, i.e. errors in the computer data. We included all the remaining trials, even though the children were not always capable of satisfying the required 18 loops per trial. In the first stage, the realized loop patterns were filtered with a second-order, dual-pass Butterworth filter. The high-pass frequency was 0.5 Hz for all signals and the low-pass cut-off frequency of the filter was set to twice the pacing frequency of the condition in which the signal was recorded. This ensured that an automatic zero-crossings detection algorithm could be applied reliably. In the second stage, the unfiltered realized data were filtered with a second-order, dual-pass Butterworth filter with a high-pass of 0.5 Hz and a low-pass cut-off frequency of 8 Hz for the automatic peak-peak detection. On the basis of this algorithm, successive cycles were extracted of which the first and last cycle of the trial were not included in the analysis.

Amplitude and frequency errors

For each obtained writing cycle, the realized vertical amplitude A, expressed in mm, in the y-dimension was calculated. A similar procedure was applied to arrive at a local cycle frequency, F, expressed in Hz. Next, the parameters A and F were used to calculate the local spatial error, A_{err}, expressed as a percentage of the instructed amplitude, where positive values reflected amplitude over-shoots and negative values reflected amplitude undershoots. Similarly, the local frequency error, F_{err}, was expressed as a percentage of the instructed frequency, where positive values reflected higher than instructed frequencies and negative values represented lower than instructed frequencies (see Fig. 1). The next step concerned quantifying the error changes from one cycle to the next. Except for the first movement cycle in each trial, we obtained for each cycle, the two parameters AA_{err} and AF_{err}, where AA_{err} equalled A_{err} of cycle i minus A_{err} of cycle i - 1, and AF_{err} equalled F_{err} of cycle i minus F_{err} of cycle i - 1. A minimum value, *d*, set at 1% of the local instructed parameter value, was used to identify a change in parameter value (see Footnote[1]). Any absolute value greater than or equal to this value qualified as a parameter-value change. We first categorized the A_{err} and F_{err} data into the eight outer (quantitative) cells of Table 1. These eight categories represented all possible combinations of overshoots and undershoots in the amplitude and frequency domain. Subsequently, each AA_{err} and AF_{err} combination, representing the error change realized from one movement to the next, was classified as a single-parameter change or as a double-parameter change or as a quasi-double-parameter change (Fig. 1). Furthermore, the axial pen pressure in Newton was determined for each obtained writing cycle.

1 We tested the effect of the minimum local instructed parameter value setting over a range of 1-5% to identify a change in parameter value. We observed no effect in identifying a change in parameter value over this range of minimum values.

Time series analysis

Continuous relative-phase time functions were inspected for branch cut crossings (phase wraps). No branch cut crossings were found. To assess how well the children performed the experimental task in synchrony with the acoustic pacing signal, we evaluated the means $(M\phi)$ and standard deviations $(SD\phi)$ of the continuous relative-phase signals of the acoustic pacing signal and the translations of the tip of the pen onto the y-dimension while using Batschelet's (1981) procedure involving circular statistics (see Meulenbroek, Thomassen, Van Lieshout, & Swinnen, 1998).

Statistical evaluation

The critical value for statistical significance was set at the .05 level. Sign tests were used to evaluate the statistical significance of observed differences between the incidences of movement-error categories and categories of parameter changes. These non-parametric tests were more conservative than Chi-square tests in this context. The formulated predictions were evaluated by means of Student's *t*-tests.

Results

Amplitude and frequency errors

On average, all children overshot the 3 mm instructed movement amplitude (3.31 mm) and undershot the 6, 9, and 12 mm instructed movement amplitude, respectively, 5.32, 7.13, and 8.96 mm. Post hoc analyses showed that the realized amplitudes could be grouped into four subsets that were significantly different. The instructed movement frequencies (1 and 2 Hz) were produced quite accurately (1.17 and 1.98 Hz) while the children lagged in producing the 3 Hz instructed movement frequency (2.64 Hz). Post hoc analyses showed that the realized frequencies could be grouped into three subsets that were significantly different.

In total, 22,668 movement cycles were evaluated with respect to the realized amplitude and frequency relative to the goal amplitude and frequency and with respect to the realized parameter change from one movement to the next. Table 1 shows the frequency distribution of performance errors categorized per cycle but collapsed over the instructed amplitude and frequency conditions. At the center of Table 1 the proportion of movements for which both the amplitude and frequency were on target. Thirty-one out of thirty-four children produced more amplitude undershoots (71%) than amplitude overshoots (27%); (sign test, N = 34, $p < .001$) while the incidence of positive (54%) and negative (46%) frequency errors proved statistically indistinguishable (sign test, N = 34, *ns)*.

Table 1. *Incidence (%) of amplitude and frequency errors.*

Frequency	Amplitude		
	Too Small (%)	No Error (%)	Too large (%)
Too High	39.11	1.76	12.25
No error	1.80	0.10	0.75
Too Low	29.81	1.27	13.73

Figure 3 shows the time course of the size of the second to eight unsigned parameter errors. The figure shows that the mean size of the amplitude and frequency error decreased sharply after the second movement cycle. Post hoc analyses showed that the amplitude error over the second movement cycle was significantly larger than over the remaining movement cycles, while the frequency error over the second and fourth movement cycles were significantly larger than over the remaining movement cycles. Amplitude errors (M = 24.77%, SD = 26.35%) were, on average, larger than frequency errors (M = 18.74%, SD = 17.89%; $t(33) = 4.122$, $p < .001$). No improvements were observed in a control analysis of between-trial error-reduction over the six repetitions per amplitude-frequency combination. On average, amplitude error size (in mm) between young graders (M = 1.85, SD = 0.64) and old graders (M = 1.86, SD = 0.71) proved statistically indistinguishable ($t(10) = 0.086$, *ns)* whilst frequency error size (in Hz) was larger for young graders (M = 0.43, SD = 0.08) than for old graders (M = 0.30, SD = 0.08; $t(10) = 3.201$, $p < .05$).

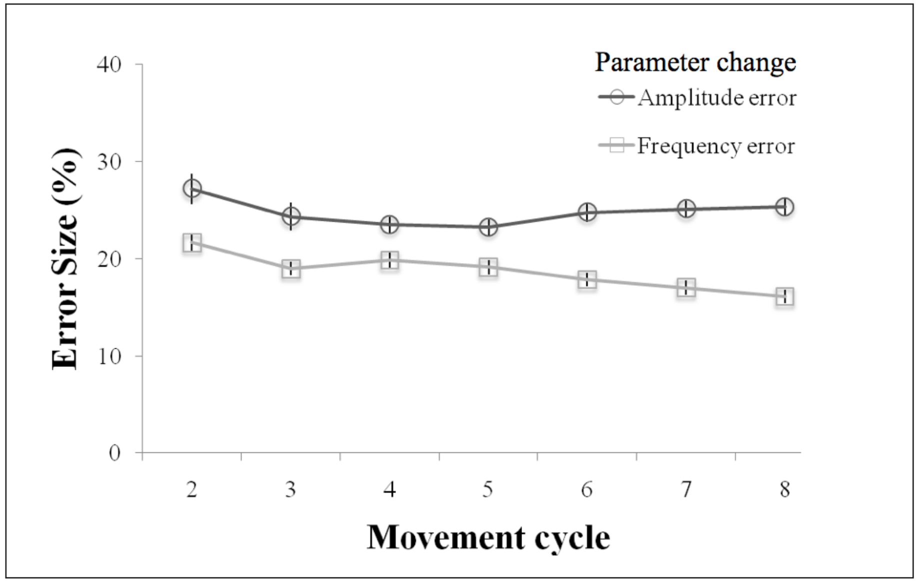

Figure 3. *Time course of the mean error size (in percentages) of the second to eight unsigned parameter errors (amplitude and frequency). Error bars represent 95% confidence intervals.*

Parameter changes from one movement to the next

Table 2 shows the incidence of the three types of parameter change as a function of the three categories of error changes (increase, increase/decrease, and decrease) expressed as a percentage of the local goal-parameter. The latter factor reflects whether the parameter changes were goal-directed (increase) or not (decrease).

Table 2. *Frequency table of parameter changes (single, double, quasi-double; see text). The row factor (error change) reflects whether the changes were goal-directed (increase) or not (decrease).*

Error change	Type of parameter change			Total
	Single (%)	Double (%)	Quasi-double (%)	
Increase	1.45	5.46	7.61	14.52
Increase and decrease	5.32	15.01	30.76	51.09
Decrease	4.02	12.00	17.75	33.77
Total	10.79	32.47	56.12	99.38

In general, the children obeyed the task instructions by trying to satisfy both the requested amplitude and frequency constraints. From one movement to the next they succeeded in changing the local movement parameters toward the goal movement parameters. Thus, all children produced more movements that reduced either one or both parameter error(s) (84.86%) than movements that caused both local movement parameters to drift away from the goal-parameter combination (14.52%; sign test, N = 34, p < . 001). As expected, an appreciable number of the moment-to-moment changes in performance were double-parameter changes (32.47%). However, all children produced more quasi-double-parameter changes (56.12%) than double-parameter changes (sign test, N = 34, p < . 001) or single-parameter changes (10.79%; sign test, N = 34, p < .001), while double-parameter changes outnumbered single-parameter changes for all children (sign test, N = 34, p < .001).

Single, double, and quasi-double parameter changes as a function of movement speed

Figure 4 shows the incidence of the single, quasi-double, and double-parameter changes as a function of movement speed. Thirty-three out of thirty-four children produced more quasi-double parameter changes (50.95%) than double (34.72%) parameter changes at the lowest movement speed (sign test, N = 34, p < .001) while for all children both quasi-double and double-parameter changes occurred more often than the single-parameter changes (13.63%; sign test, N = 34, p < .001).

Thirty-one out of 34 children produced less quasi-double parameter changes in the 1 Hz mode (50.95%) than in the 3 Hz mode (61.81%; sign test, N = 34, p < .001). In contrast, 24 out of 34 children produced more double-parameter changes in the 1 Hz mode (34.72%) than in the 3 Hz mode (29.32%; sign test, N = 34, p < .05). The incidence of single-parameter changes was higher, for 30 out of 34 children, in the 1 Hz (13.63%) mode than in the 3 Hz mode (8.50%; sign test, N = 34, p < .001).

Time series analysis

The standard deviation of the relative phase between the acoustic pacing signal and the translations of the tip of the pen onto the y dimension (SDϕ in deg) as a function of imposed amplitude was only larger for the 3 mm amplitude (M = 66 .96, SD = 6 .14) than for the 6 mm (M = 64 .05, SD = 8.11; t(33) = 3.338, p < .05) and 12 mm amplitudes (M = 64.09, SD = 8.12; t(33) = 3.098, p < .05). $SD\phi$ was larger for the 3 Hz mode (M = 68.04, SD = 9.78) than the 1 Hz (M = 64.63, SD = 7.47; t(33) = 2.225, p < .05) and 2 Hz modes (M = 62.46, SD = 8.60; t(33) = 3.848, p < .05). While the mean relative phase between the acoustic pacing signal and the vertical translations of the tip of the pen ($M\phi$ in deg) for younger first graders (M = 87.31, SD = 10.79) and older first graders (M = 90.85, SD = 19.81) proved statistically indistinguishable (t(11) = .634, ns), the $SD\phi$ was larger for younger first graders (M = 70.43, SD = 4.58) than for the older first graders (M = 61.20, SD = 8.37; t(11) = 2.787, p < .0 5). Furthermore, only the $SD\phi$ for younger first graders in the 3 Hz mode (M = 7 5 . 24 , SD = 4.21) was larger than the 1 Hz (M = 67.98, SD = 8.49; t(11) = 2.343, p < .05) and 2 Hz modes (M = 68.15, SD = 8.06; t(11) = 2.759, p < .05).

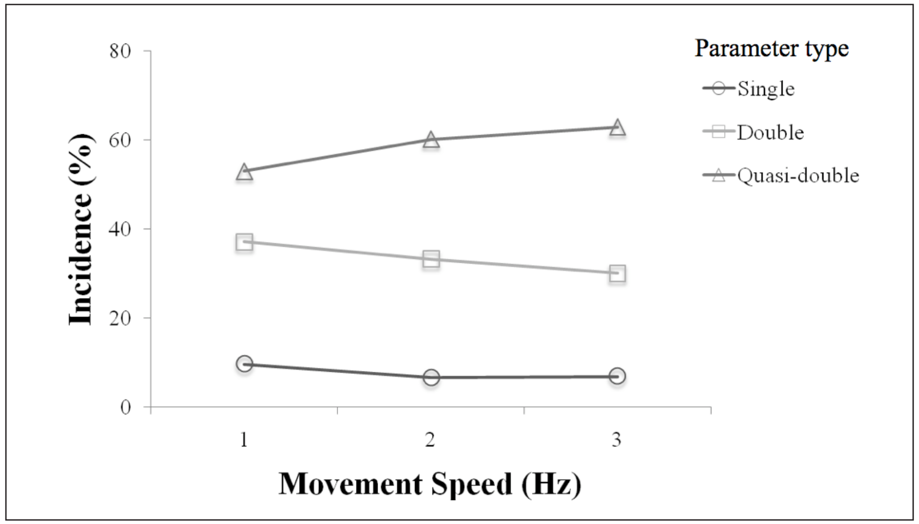

Figure 4. Incidence (in percentages) of single, double, and quasi -double-parameter changes as a function of movement speed (1 Hz, 2 Hz, and 3 Hz).

Discussion

This study was concerned with how preparatory writers vary the amplitude and frequency of their cyclical handwriting movements in a task in which both parameters were set as targets. The aim was to distinguish parameter changes that reflected the exploitation of biomechanics from those that required deliberate control to override natural biomechanical tendencies.

We found that most movement-to-movement parameter changes (56.12%) were quasi-double-parameter changes and, as such, can be said to have resulted from exploiting (or following) natural biomechanical tendencies. The high incidence of such changes is consistent with Bernstein's (1967) view that adaptive motor behavior entails exploitation of, rather than resistance to, physics but goes against our expectations that were based on the proposed learning phases by Fitts and Posner (1967). Fewer movements (10.79%) resulted from single-parameter changes while an appreciable number of movements were double-parameter changes (32.47%; Table 2), which we took to reflect deliberate control because the resulting movements entailed overriding natural amplitude-frequency relationships.

Amplitude errors were, on average, larger than frequency errors indicating that children were more tolerant of amplitude errors than of frequency errors, perhaps because of differences in acuity for the two kinds of signals (see also Thomas & Moon, 1976). Furthermore, children typically produced more undershoots than overshoots (71% versus 27%), reminiscent of other smaller-than-required amplitudes in studies of aiming and possibly indicative of a strategy in which children gradually decreased the percentage of undershoots and "sneaked up" on the target as part of a "play-it-safe" approach (see Elliot, Hansen, Mendoza, & Tremblay, 2004; Engelbrecht, Berthier, & O'Sullivan, 2003).

In general, preparatory writers are only trained to write within different-sized, staved training lines. In our experiment children were asked to comply with both frequency and amplitude constraints at the same time, therefore the task at hand can be viewed as a novel task. Considering this fact, one could theorize that about 32% of the movements reflected deliberate and thus cognitive control, which in terms of motor learning could be seen as performing in the cognitive phase as stated by Fitts and Posner in their three phased view of motor learning. In the cognitive phase the major gains lie in the knowledge of what is to be done and is referred to as verbal cognitive in nature. In the first 16 try-outs of the task they captured the way to handle the different timing and spatial constraints and could be said to enter the associative phase of adjusting to the task load. The associative phase begins as the learner has determined the most effective way of executing the task and starts to make more subtle adjustments in how the skill is performed. In an earlier description of motor learning stages, Adams (1971) used a two-staged view, consisting of a (more) verbal motor stage and an (more) action motor stage. It is well possible that higher percentage of quasi-double-parameter changes, combined with a still appreciable number of double-parameter changes, reflects the transition from cognitive to associative learning phase, or as Adams suggested, from a verbal to a motor performance stage in which the children use more differentiation in timing and learn to use spatial constraints. It might be possible that not all the children were able to pick up the best strategy or were at lost for a strategy while forced to repeat the movements.

While children, in comparison to the results in the study of Bosga et al. (2005), were able to produce a comparable amount of movements that entailed overriding natural amplitude-frequency relationships (32.47% versus 30.08%), a striking observation of the present study is that children produced nearly three times less single-parameter changes than adults (10.79% versus 26.64%). Consequently children produced more quasi-double-parameter changes than adults (56.12% versus 41.37%). At the lowest movement speed (1 Hz) children produced 13.63% single-parameter changes as opposed to the 18.62% of adults, while at 3Hz, the percentage of single-parameter changes for adults (26.31%) was more than three times higher than single-parameter changes for children (8.50%). Both quasi-double and double-parameter changes reflect the coupling of parameter changes in the amplitude and frequency dimension during a movement cycle. Single-parameter changes therefore presupposes the uncoupling of parameter changes in both dimensions during a movement cycle, i.e., a movement change is produced in one dimension while simultaneously no movement change in the other dimension is realized. It seems that resorting to single-parameter changes constitutes a good strategy to cope with time pressure because at higher movement speeds people only have to adjust their movement in one dimension and reproduce the previous error in the other dimension. Intrinsic dynamics in a given situation depends, among others, on the natural tendencies of the system, i.e., in this study, a tendency to primarily exploit the inverse amplitude-frequency relationship. This coordination bias often emerges during the acquisition of complex skills that entail an accepted pattern or technique (Walter & Swinnen, 1994). Zanone and Kelso (1992) have shown that learning leads to important alterations of the intrinsic dynamics: new attractors appear, and a transitory destabilization of more natural patterns was observed. Obviously, for children to become efficient writers they must also learn to overcome the natural biomechanical tendencies of the system.

Even though the preparatory writers in this study were in the initial phase of commanding letter shapes and spelling they were, in contrast to our predictions, quite capable of producing movements that reflected the exploitation of biomechanics. Furthermore, they produced more movements that reduced either one or both parameter error(s) than movements that caused both local movement parameters to drift away from the goal- parameter combination. That the relative frequencies of the different kinds of parameter changes reflected strategic influences was supported by the dependence of the parameter changes on movement speed. As seen in Fig. 4, preparatory writers produced more quasi-double-parameter changes at the highest movement speed (3 Hz) than at the lowest movement speed (1 Hz). In contrast, double-parameter changes were produced less often at the highest movement speed than at the lowest movement speed. These observations indicate that preparatory writers can, as predicted, pursue multiple movement goals simultaneously at lower speeds while at higher speeds their capacity to satisfy multiple task goals is reduced.

Phase relationships between the acoustic pacing signal and the vertical translations of the tip of the pen, were comparable between younger and older first graders (~90°). This means that all children evenly lagged behind with their pen movement to the acoustic signal, thereby displaying reactive coordination with their movements to the pacing signal. However, the stability of the phase relationship between the acoustic signal and pen movements was larger for old graders than for young graders (~70° versus ~61°). This observation is, together with our finding that in general older children demonstrated a tighter frequency locking than younger children, in line with findings of Volman and Geuze (2000) showing that relative-phase dynamics underlying perception-action coordination patterns change with age in the direction of an increased temporal stability. Interesting to note is that in their study on lifespan sensorimotor synchronization using a tapping task, Drewing, Aschersleben and Li (2006) found that the ability to produce one tap near each click progressively develops from 6 until the age of 15 years and the variability of basic timekeeping decreases during childhood. In their 6-8 year old group, 50% of the children were extremely asynchronous, while the temporal match between taps and clicks improved with age. The results in the present study show that younger first graders produced larger frequency errors than older first graders (0.43 Hz versus 0.30 Hz). These frequency errors were mostly seen in the 3 Hz frequencies in combination with 3 mm amplitude domain. The combination "fast" and "small" involves learning to make the correct movement under time pressure which needs both fine distal movements of the fingers and less reliance on visual control. While comparing younger and older first graders, especially the younger group might not be mature enough to be able to organize the multiple degrees of freedom of the finger hand movements and in the same time to rely less on the afferent visual feedback used in this closed loop skill of loop-writing. We presume that the older first graders could utilize a more mature sensorimotor synchronization mechanism to improve performance in the temporal domain. The accumulation of evidence which indicates that, on average, the younger children of a year group, perform lower on cognitive and motor attainments than the older children, provided us with an opportunity to view

learning and maturation on the level of age position in the classroom (McPhillips & Jordan-Black, 2009). The difference between these younger and older children in cognitive and motor attainment is known as "the birth-date effect". Birth-date effects decrease in later grades, are most pronounced in primary school age and particularly strong in kindergarten and grade one (Sykes, Bell, & Rodeiro, 2009). It is clear that, even within a single school grade, behavioral performance changes as a result of maturation.

In sum, seven-year-old preparatory writers were quite efficient in changing the local movement parameters toward the goal-parameters while generally undershooting the amplitude requirements. However, between-trial learning effects of parameter error-reduction over the six repetitions per amplitude-frequency combination were absent. Surprisingly, children relied mostly on a control strategy that reflected the exploitation of natural biomechanical tendencies and were, as expected, capable of satisfying multiple constraints at low movement speeds. Finally, the influence of maturation should be taken into account when constructing a curriculum for handwriting, because older first graders produced smaller frequency errors as a result of stronger perception-action coupling. Although the birth-date effect is generally used as an indication of cognitive and motor performance of summer-born children (June to August), the influence of maturation is a general effect found across large groups of pupils and should not be underestimated.

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Chapter 3

Developing Movement Efficiency between 7 and 9 Years of Age

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Developing Movement Efficiency between 7 and 9 Years of Age

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Abstract

This longitudinal study examined the movement efficiency of typically developing children between 7 and 9 years of age by scrutinizing their movement amplitudes and frequencies as they settled into a loop-writing task in which both parameters were prescribed. It was hypothesized that during the first three grades at primary school children would show increasing efficiency in exploiting the inverse relationship between movement amplitude and frequency when adjusting their movement errors. Whereas a clear developmental trend showed increasing efficiency with respect to the way in which the primary school children met the amplitude constraints, a more variable pattern was found for the age-dependent adjustments to the frequency requirements. At the level of parameter-error corrections from one cycle to the next, a marginal developmental trend was observed. Results are discussed in terms of contrasting effects between educational targets and movement-efficiency principles.

Introduction

The study of efficiency principles in human movement control has a long history. The systematic relationships that exist between spatial and temporal movement parameters have been captured in principles such as Isochrony (Viviani & Terzuelo, 1980; Viviani & McCollum, 1983), Isogony, the two-thirds power law (Lacquaniti, Terzuelo, & Viviani, 1983) and the speed-accuracy trade off known as Fitts Law (Fitts, 1954).

In many everyday motor tasks multiple goals need to be achieved simultaneously. For example, speed and accuracy always are competing task constraints even though they are inversely related. In the face of such conflicts, it would be effective if one could find an efficient way of serving multiple purposes simultaneously. Some repetitive motor tasks allow for such a strategy. In cyclical motor tasks that need to be performed at a prescribed amplitude and frequency, the actor can strategically focus on changing one of the parameters to keep its value within acceptable boundaries while allowing the other to covary passively (Bosga-Stork, Bosga, & Meulenbroek, 2011). Given people's limited processing capacity (Hazeltine & Wifall, 2011) such a strategy seems more efficient than trying to continuously monitor and adjust both parameters simultaneously.

In a recent study we investigated the error-correction strategies from one movement to the next that primary school children adopt in a cyclical handwriting task with prescribed amplitude-frequency combinations (Bosga-Stork et al., 2011). We found that young children in first grade (at the age of 7) were able to exploit the inverse relationship between amplitude and frequency that follows from Fitts' law, particularly when they were pressed for speed. The changes of the movement parameters during task performance were more frequent in line with the inverse relationship than not, indicating that children also adopted a strategy of changing one of the parameters to reach a target value and let the other parameter covary passively. This left the question unanswered as to how such performance strategy develops with age. To answer this question we asked in the present longitudinal study the same group of children in second and third grade (8 and 9 years of age), to perform the same loop-writing task with prescribed amplitude-frequency combinations as used when they were 7 years old (Bosga-Stork et al., 2011). To what extent do children manage to contain their movement errors within an acceptable range as they develop from preparatory writers into more experienced writers (Meulenbroek & Van Galen, 1988)? How do they achieve such control? We used the same target amplitude-frequency combinations as in our previous study (Bosga-Stork et al., 2011).

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The diagram of the design of our study depicted in Fig. 1 shows the four different amplitude and three frequency conditions. The drawing performances over the two years of follow-up were recorded.

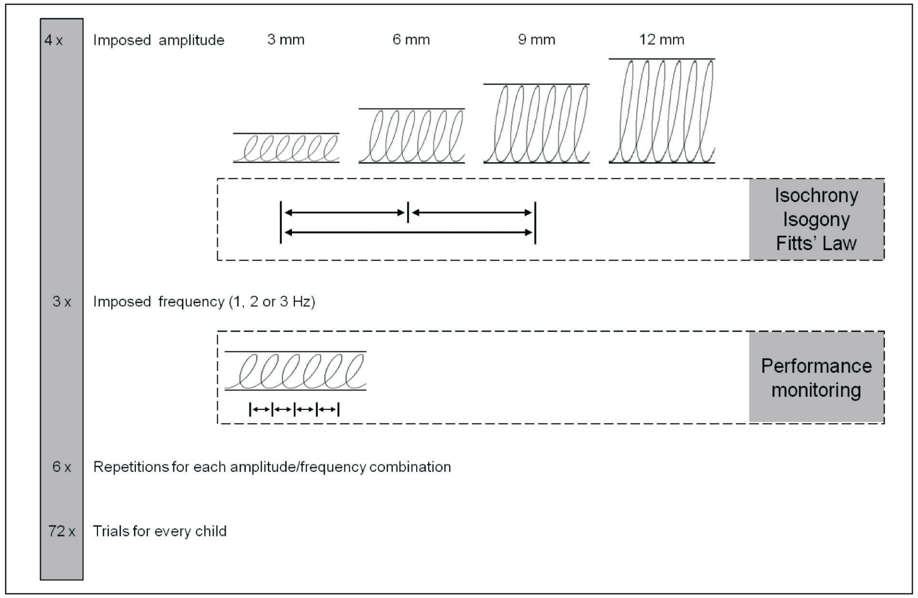

Figure 1. *Four different amplitude instructions were used (3mm, 6mm, 9 mm, and 12 mm), in combination with three frequency instructions (1 Hz, 2Hz, 3 Hz). These combinations amounted to 12 two-parameter combinations. Each combination was repeated six times (each trial consisting of 18 cycles), which resulted in a total of 72 trials for each child. The experiment was presented three years in a row, at ages 7 (Grade 1), 8 (Grade 2), and 9 (Grade 3) and performed monitoring per cycle was scrutinized, which gave a window in development (mean of all cycles) and adaptation (second, third, and fourth cycle), respectively.*

In the present study we analyzed our longitudinal data on two different time scales, thus both providing a window into global development and into local task adaptations (Thelen, 2005; Von Hofsten, 2004). Development, generally referring to long-term behavioural changes due to maturation, growth and learning, is here studied in the first three years of primary school covering the period of handwriting development from preparatory to experienced handwriting. With task adaptation we refer to the way people locally alter an individual movement of a specific action sequence to accommodate the constraints of the task at hand (Magill, 2011; Morris, 2009; Shumway-Cook & Woollacott, 2007). We presume that the child actively explores a given task and detects information to adjust his or her performance to achieve the task goals (Dusing & Harbourne, 2010). We capture adaptation by assessing the kinematic adjustments to the amplitude and frequency demands on a cycle-to-cycle basis within the first few counterclockwise rotating loop patterns. A description of the categorization of the cycle-to-cycle parameter-error changes that we distinguished can be found in Bosga-Stork et al. (2011). We have summarized this categorization in Figure 2, which is described in detail in the Methods section. Suffice to restate here that we distinguished between efficient and inefficient movement-error corrections depending on whether the cycle-to-cycle parameter changes were in line with the inverse relationship between amplitude and frequency or not.

Two hypotheses were formulated. One of the results of our earlier study was that older first graders (differentiating between old and young pupils on birthday) produced smaller frequency errors as a result of stronger perception-action coupling (Bosga-Stork et al., 2011). Therefore we expected that the children, when being re-assessed in the second and third grades of primary school, would become gradually more skilled in exploiting the inverse relationship between movement amplitude and frequency (Newell & Van Emmerik, 1989; Newell, 1986; Fitts & Posner, 1967).

Secondly, with respect to how the children would contain their movement errors in the first part of the loop-writing task, we assumed that children, like adults, would settle into the task quickly, evidenced by decreasing performance errors in the second, third and fourth cycles (cf. Fig. 3 in Bosga, Meulenbroek, & Rosenbaum, 2005). Furthermore, we expected the children to increasingly exploit the inverse relationship between amplitude and frequency while adjusting their movement parameters on a cycle-to-cycle basis, as they develop from preparatory writers into more experienced writers.

Method

Participants

A total of 34 typically developing primary school children were included in this study[1]. At the start of this study they resided in two different first grade groups of two allied schools. The same cohort, was followed over two years: starting as preparatory writers attending 1st grade, as first-year writers attending 2nd grade and as trained writers attending 3rd grade. The group consisted of fifteen girls and seventeen boys with a mean age of 7.1 (M = 7.1, range 6.4 - 7.6) in Grade 1. The children were tested each year in April. All participants had normal hearing and normal or corrected-to-

1 *During the course of the study 2 children left school. The longitudinal study here (and in the following chapters) involved 32 children.*

normal vision. Each year all parents of the participants gave their informed consent. Each child received a little present after the experiment. Experimental procedures followed the APA guidelines for the ethical treatment of human participants.

Procedure

The experiment consisted of a writing task that was performed on a digitizer tablet. The same experiment was repeated twice in a two-year time-span. The children were tested each year by the same experimenter (I.B-S, first author). The experiment took place in a separate, quiet and well-lit room at the schools. The children were seated on an adjustable chair, with their feet supported and in a writing position adapted to the digitizer tablet. Participants were required to write loop patterns with an electronic ink pen (Intuos3) on preprinted sheets of paper attached to a digitizer tablet (WACOM A4 Oversize tablet). The loop patterns height was either within 3, 6, 9 or 12 mm lineation and the task was paced by an acoustic signal of either 1, 2 or 3 Hz. The pacing signals changed sinusoidal in intensity across a clearly audible range (approximately 60-70 dB; tone pitch 330 Hz). Each of the 12 preprinted trial sheets consisted of six repetitions (block) of the twelve amplitude-frequency combinations and was presented at random. Amplitude-frequency combinations within the six trials of a block remained constant. Each child was asked to perform 72 trials of 18 loops each, leading to a theoretical total of 1296 loops per experiment at age 7, 8 and 9 (i.e. a maximum of 3888 loops per child). On-line recordings of X, Y and Z (axial pen force) were sampled at 200 Hz (Bosga-Stork et al., 2011). Before the experiment started, the task was explained and the participants were allowed to perform the task a few times to get comfortable with experimental procedures and task requirements. For this purpose, each of the three frequencies was practice twice, using the 9 and 12 mm loop patterns, thus yielding 12 practice trials, in grade one. In grades two and three each of the three frequencies was practiced twice, using only the 9-mm loop pattern (6 practice trials) since all children recognized the task and remembered what the procedure was.

Data Analysis

All data were visually inspected. After inspection, 224 trials (1.06%) were rejected in the first experiment, 130 trials (0.49%) in the second and 65 trials (0.23%) in the third experiment. This was either due to missing data points when the children were taken by surprise by the pacing sound at the start of a trial or lagged behind the pacing signal too much during loop writing. To avoid artefacts due to smoothing by

means of the Butterworth digital filter, we excluded the first and last cycle of each trial in the filtering. If the children were not able to comply with all 18 loops of a trial, the realized cycles of these trials were included. Execution of fewer cycles than instructed was either due to slowness in starting or executing a particular trial. In total 76,231 movement cycles (7 years: 21,092; 8 years: 26,669 and 9 years: 28,470) were evaluated in terms of realized amplitude and frequency relative to the goal amplitude and frequency, and with respect to the realized parameter change from one movement to the next. To allow zooming in on the settling-in process in each trial, we selected the second, third and fourth cycles in our error analyses[2].

The procedure of filtering the digitized pen-tip movements was identical to the one reported earlier (Bosga-Stork et al., 2011).

Amplitude and Frequency Errors

The realized vertical amplitude (A expressed in mm) and local cycle frequency (F expressed in Hz) were calculated for each writing loop. Following the procedure used earlier we calculated the local, signed parameter errors (A_{err} and F_{err}). The absolute error (AE) of the amplitude and frequency (AE_{amp} and AE_{frq}) was calculated as the unsigned error expressed as a percentage of the instructed amplitude and frequency. Next, we calculated on the basis of the *signed* errors, the error changes from one cycle to the next. From each cycle, except the first, the two parameters ΔA_{err} and ΔF_{err} were determined where ΔA_{err} equalled A_{err} of cycle i minus A_{err} of cycle i-1, and ΔF_{err} equaled F_{err} of cycle i minus F_{err} of cycle i-1. A minimum value, d, set at 1% of the locally instructed parameter value, was used to identify parameter changes. Any absolute value greater than or equal to this value qualified as a parameter change. We first categorized the A_{err} and F_{err} data into eight error types, which represented all possible combinations of overshoots and undershoots in the amplitude and frequency domain. Around a hypothetical goal eight possible performance errors might occur (see Fig.2). In a particular loop, a child can either make a single-parameter error (either amplitude or frequency is off-target: A^0F^+, A^+F^0, A^0F^- and A^-F^0) or a double-parameter error (both amplitude and frequency are off-target: A^+F^+, A^+F^-, A^-F^- and A^-F^+). The rationale for this classification is fully described in Bosga-Stork et al. (2011). In short it is based on the fact that large-amplitude arm movements tend to be performed at low frequencies by means of shoulder and elbow rotations, whereas small-amplitude arm movements tend to be performed at higher frequencies by means of wrist and finger rotations (Rosenbaum, Slotta, Vaughan,

2 In a separate analysis involving all cycles we did not find a different pattern of results.

& Plamondon, 1991; Vaughan, Rosenbaum, Diedrich, & Moore, 1996). In a task where the participants are forced to depart from these movement patterns (e.g. to produce fast shoulder movements or slow wrist rotations), they cannot rely on these intrinsic amplitude-frequency relationships and instead have to activate less natural, possibly more attention-demanding control regimes (cf. Zelaznik, Spencer, & Ivry, 2002; Bosga et al., 2005).

To capture the efficiency with which the children changed their movement-parameter errors from cycle to cycle, we determined the ratio of the incidence of double-parameter changes that were in line with the inverse relationship between amplitude and frequency (A^+F^- and A^-F^+) over the incidence of parameter changes that were at odds with the inverse amplitude-frequency relationship (A^+F^+ and A^-F^-).

A ratio larger than 1.0 reflected efficient corrections of movement-parameter errors. In the remainder of this article we refer to this ratio as the efficiency index.

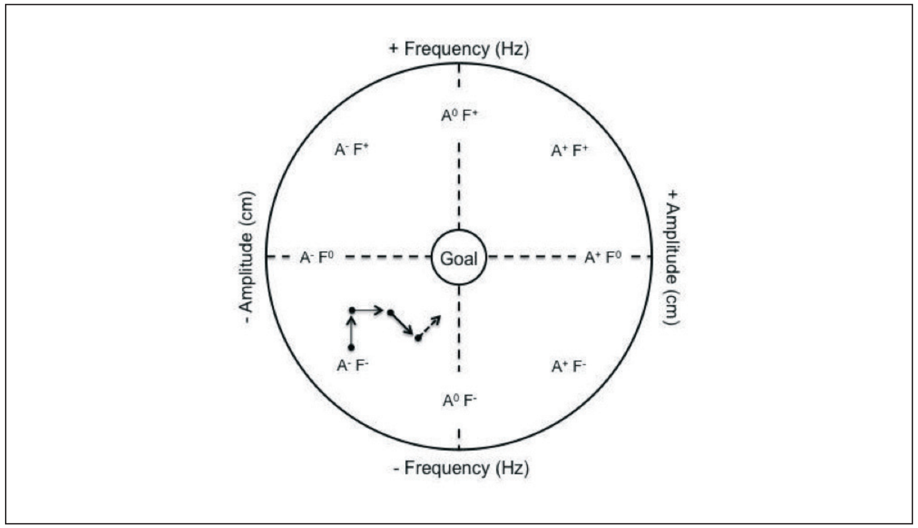

Figure 2. *Possible changes in performance in successive cycles. The sequence of the arrows toward the goal in the center depicts a hypothetical series of transitions in amplitude-frequency space, beginning with amplitude that is too small (A^-) and a frequency that is too low (F^-). The first arrow pointing upwards represents a single parameter change (and error reduction) in the frequency domain; the second arrow pointing rightward represents a single parameter change (error reduction) in the amplitude domain. The third arrow (bold) represents a double parameter change (of which the amplitude change is an error reduction and the frequency change an error increase) and the fourth arrow (bold dashed) indicates a quasi-double parameter change: both the amplitude and frequency errors are reduced ant this compound error reduction corresponds with the inverse relationship that exists between amplitude and frequency.*

Statistical evaluation

Two repeated measures ANOVAs on the errors of the realized amplitudes and frequencies separately were performed. For the amplitudes we used a two-factor within subjects-design consisting of Age (7, 8, 9 years)[3] and Instructed Amplitude (3, 6, 9 and 12 mm), for the realized frequencies we used a design consisting of Age (7, 8, 9 years) and Instructed Frequency (1, 2, 3 Hz).

The degree to which the inverse relationship between movement amplitude and frequency was reflected in the average performance of the participants was evaluated in two separate repeated measure ANOVAs. The first ANOVA concerned the realized frequencies as a function of instructed amplitudes using a two-factor within-subject design consisting of Age (7, 8, 9 years) and Amplitude (3, 6, 9 and 12 mm). The second ANOVA was directed at the realized amplitudes as a function of the imposed frequency. Again, we used a two-factor within-subject design consisting of Age (7, 8, 9 years) and Frequency (1, 2, 3 Hz).

The degree to which the inverse relationship between movement amplitude and frequency was exploited while settling in into the loop-writing task was analyzed by evaluating the efficiency index (see Method section) by means of a univariate repeated measures ANOVAs, using a full-factorial design consisting of the two within-subject variables Age (7, 8, 9 years) and Cycle (2nd, 3rd and 4th).

For all ANOVAs held that if the Mauchly test of sphericity was violated, the Greenhouse-Geisser corrected *F* and *p*-values were chosen to evaluate within-subject effects, but to facilitate legibility we report the uncorrected *dfs* of the *F*-values. The critical value for statistical significance was set at .05. An α-value of .10 was taken to reflect a weak developmental trend. Two-tailed *t*-tests (α= 0.05) were applied for post-hoc age comparisons.

Results

Global task performance

The children were able to follow the amplitude instructions of 3, 6, 9 and 12 mm quite accurately ($F(3.93) = 955.14$, $p = .0001$. Post hoc analyses (Scheffé tests) showed that the realized amplitudes differentiated in four different categories (0.5, -0.43, -1.36, and -2.27 mm).

3 *Given the rationale described in the Introduction of this thesis, categorizong the participants into Grades (1, 2, and 3) rather than in Age groups (7, 8, and 9) seems warranted. Even though using age or grades had implications for the inferences drawn from the results, it does not have any effect on the data analysis.*

The left panel of Figure 3 shows the constant error of amplitude of the children. The main effect of Age was significant, ($F(2,62) = 5.3$, $p = .01$), the interaction between Age and Amplitude, however, was not significant ($F(2,186) < 1$, $p = .076$). At ages 7, 8 and 9, the children displayed overshoots of the 3 mm instructed amplitude (+.67, +.46, +.36 mm, respectively), small undershoots of the 6 mm instructed amplitude (-.34, -.47 and -.49 mm, respectively), and larger undershoots of the 9 and 12 mm instructed amplitudes (-1.43, - 1.28, -1.36 mm, and -2.57, -1.97, -2.28 mm, respectively).

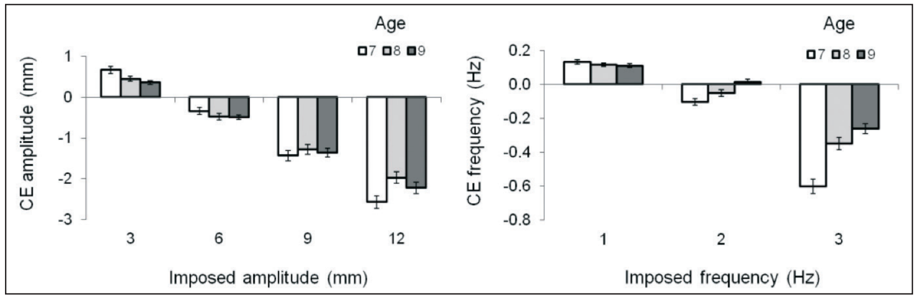

Figure 3. *Constant error for amplitude and frequency of the children at age 7, 8, and 9. In the left panel the bar chart depicts the constant error of the realized amplitude in mm as a function of the instructed amplitude (3, 6, 9, and 12 mm). In the right panel the bar chart shows the constant error of the realized frequency in Hz as a function of the instructed frequency (1, 2, and 3 Hz). The vertical lines depict standard errors of the means.*

The children were also able to reproduce the frequency instructions of 1, 2 or 3 Hz ($F(2,62) = 492.82$, $p = .0001$). Post hoc analyses (Scheffé tests) showed that the realized frequencies differentiated in three different categories. At ages 7, 8 and 9, the instructed frequencies of 1 and 2 Hz were produced with small overshoots and undershoots (1 Hz: +.13, +.12, +.11 Hz, respectively; 2 Hz: -.10, -.05, +.01 Hz, respectively) but the 3 Hz frequency was reproduced with systematic undershoots (-.60, -.35, -.26 Hz).

The constant error of frequency is shown in Figure 3 (right panel). The main effect of Age was significant, ($F(2,62) = 21.43$, $p = .0001$), as was the interaction between Age and Frequency ($F(4,124 = 11.04$, $p = .0001$).

Generally, these results show that the children were able to perform our task as instructed, with efficiency increasing with age.

Amplitude-frequency relationships

The left panel of Figure 4 displays the realized frequency as a function of Age and Imposed Amplitude. The Age effect was statistically significant ($F(2,62) = 13.74$, $p = .0001$), as was the effect of Amplitude ($F(3,93) = 7.80$, $p = .0001$). There was no interaction between Age and Imposed Amplitude ($F(6,186) < 1$, $p = .663$).

The realized amplitude as a function of Age and Imposed Frequency is displayed in the right panel of Figure 4. Here the Age effect was not statistically significant ($F(2,62) < 1$, ns), nor was the effect of Frequency ($F(2,62) = 3.491$, $p = .056$), although there was a weak trend toward significance. There was a significant interaction between Age and Imposed Frequency ($F(4,124) = 3.910$, $p = .018$). The distribution showed a U-shaped profile (the quadratic trend was significant) with amplitudes somewhat lower for the middle frequency. Generally, these results show that the children were sensitive to the inverse relationship between movement amplitude and frequency even though their response to imposed frequencies was slightly more complicated than to changing amplitude requirements.

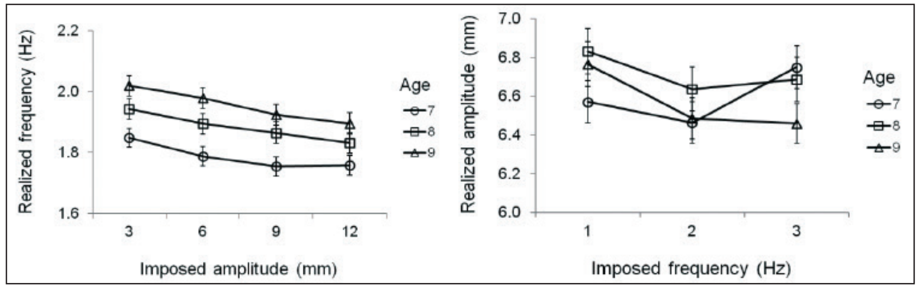

Figure 4. *Overall performance for the double parameter efficiency. In the left panel the realized frequency in Hz is shown as the result of the instructed amplitude in mm and the different ages (7,8, and 9). In the right panel the realized amplitude in mm is shown as the result of the instructed frequency for the three ages. In both panels the vertical lines depict the standard error of the means*

Error Analyses

Single-parameter errors: Amplitude

Figure 5 (left panel) displays the absolute error of the realized amplitude as a function of Age and Cycle. The Age effect was statistically significant ($F(2,62) = 11.37$, $p = .0001$) as was the effect of Cycle ($F(2,62) = 79.58$, $p = .0001$). The analysis revealed a significant interaction between Age and Cycle ($F(4,124) = 5.25$, $p = .008$). These results show that the children were able to settle quickly into the task, leveling out at a stable and acceptable spatial performance in only two cycles. The ability to realize the required amplitudes improved over the years.

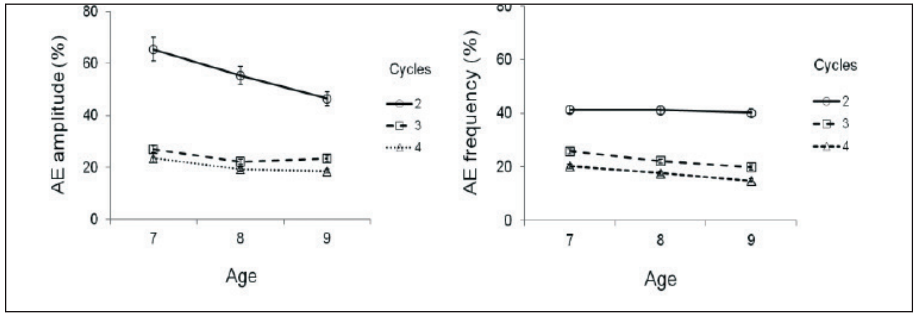

Figure 5. *Percentage of absolute amplitude errors (AE amplitude; left panel) and absolute frequency (AE frequency; right panel) as a function of age (7,8, and 9 in years) and cycle (2,3, and 4). The vertical lines depict the standard error of the means.*

Single-parameter errors: Frequency

Figure 5 (right panel) shows the absolute error of the realized frequency as a function of Age and Cycle. The Age effect was statistically significant ($F(2,62) = 9.21$, $p = .0001$) as was the effect of Cycle ($F(2,62) = 348.00$, $p = .0001$). The analysis revealed a significant interaction effect between Age and Cycle ($F(4,124) = 4.68$, $p = .007$).

These results show that the children were able to settle quickly into the task, leveling out at a stable and acceptable performance in only two cycles. Their reproduction of the imposed frequency marginally (but significantly) improved with age.

Double-parameter errors: Amplitude and Frequency

Figure 6 depicts the results regarding the efficiency index (see Method section) revealing a statistically significant developmental trend. The main effect of Age was $F(2,62) = 3.639$, $p = .043$. Cycle proved statistically significant ($F(2,62) = 56.556$, $p = .0001$) but there was no interaction between Age and Cycle ($F(4,124) <1$, ns). Overall, the efficiency index decreased with age: for 7 years ($M = 2.15$, $SD = 0.76$), for 8 years ($M = 1.95$, $SD = 0.60$) and for 9 years ($M = 1.88$, $SD = 0.51$). The index changed significantly between the ages 7 and 8 (paired $t(95) = 3.531$, $p = .013$), but was not significantly different for ages 8 and 9. The index also decreased within the first three cycles (Cycle 2: $M = 2.34$, $SD = 0.90$; Cycle 3: $M = 1.88$, $SD = 0.57$; Cycle 4: $M = 1.76$, $SD = 0.44$) where the largest difference occurred between Cycles 2 and 3 (paired $t(95) = 4.997$, $p = .0001$) and only a weak tendency to significance was found between Cycles 3 and 4 (paired $t(95) = 1.944$, $p = .055$).

These results show that the efficiency index remained fairly stable over the years and was most pronounced during the early cycles of our loop-writing task.

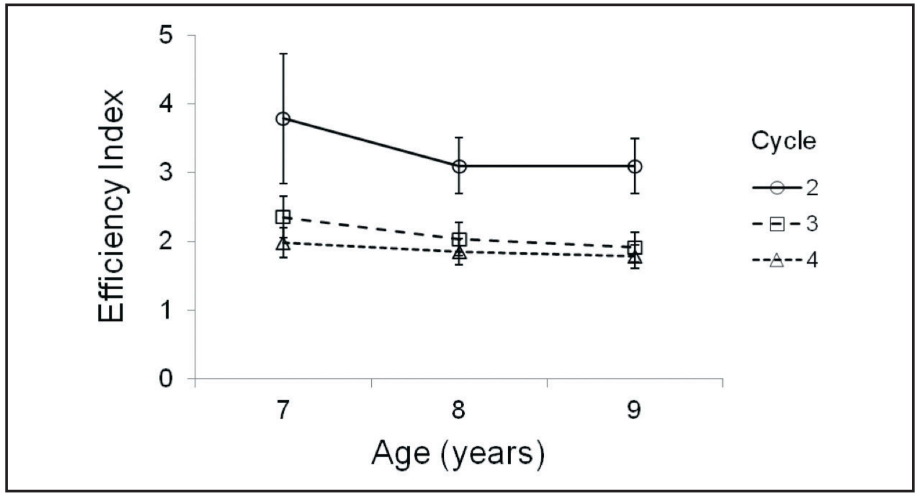

Figure 6. *The efficiency index as a function of age (7, 8, and 9 years) and cycle (Cycle 2, 3, and 4). The efficiency index is defined as the ratio of biomechanical - over intentional parameter error changes. When the ration is >1.0, the error corrections is in line with the inverse relationship between amplitude and frequency; see text). The vertical lines depict the standard error of the means.*

Discussion

Research question

The present longitudinal study analyzed the efficiency with which primary school children at age 7, 8 and 9 try to simultaneously meet spatial and temporal movement instructions while settling into a loop-writing task. We analyzed (i) how well the children reproduced the instructed amplitudes and frequencies, (ii) whether their behavior reflected the inverse amplitude-frequency relationship, and (iii) the extent to which they exploited this relation when correcting errors from cycle to cycle while settling into the task. Before discussing our main findings it must be noted that we did not expect qualitative changes in performance as, for example, reported by Peper and Beek (1998) since we studied effects of a fairly small, educationally relevant range of parameter changes.

Developing efficiency

As regards the realized amplitudes the primary school children displayed systematic undershoots of up to 25% of the instructed loop sizes, thus reflecting the general tendency of people to perform undershoots of spatial targets. Such a tendency has been attributed to energy containment (Elliot, Hansen, Mendoza, & Tremblay, 2004). These findings are in line with the results found by Vinter and Mounoud (1991). Among the four amplitudes tested the 3 mm amplitude stood out, since at all ages the children overshot this amplitude. Apparently, the smallest amplitude required too much movement precision for the children to perform accurately (Trap-Porter, Gladden, Hill, & Cooper, 1983). When asked for their opinion, they expressed that the 6 mm amplitude was the easiest amplitude to produce. Developmentally, the children systematically improved in amplitude reproduction with age.

It seems reasonable to expect older children to realize the required loop amplitudes more efficiently than younger children because between the ages of 7 and 9 their hands grow larger. However, we do not consider this line of reasoning correct. The argument may hold if the loop-writing task would be performed by the hand only, i.e. through wrist and finger movements but earlier studies have shown that even adults involve pro-supinations, forearm rotations and (moderate) shoulder excursions in loop writing tasks involving amplitude sizes as applied here (Meulenbroek, Thomassen, Lieshout, & Swinnen, 1998; Meulenbroek, Rosenbaum, Thomassen, & Schomaker, 1993). Furthermore, in the present loop-writing task we did not impose constraints on limb-segment involvement. We therefore attribute the age-dependent improvement in amplitude reproduction to increased movement efficiency.

As concerns the realized movement frequencies the children performed the 2 Hz frequency most accurately. The 1 Hz frequency was performed too fast and the 3 Hz frequency too slow. These results replicate earlier findings concerning preferred movement frequencies in cyclical drawing behavior in adults (Meulenbroek et al., 1993) and are compatible with models capitalizing on the role of preferred amplitudes and frequencies and cognitive efficiency constraint in movement selection (Rosenbaum et al., 1991). When asked, the children were upfront in their opinion that the 2 Hz speed instruction was the easiest to comply with. As regards development, the 3 Hz frequency stood out because it showed an error reduction of

33 % between the ages of 7 and 9. In general, the children thus became more skilled in attaining the highest, acoustically instructed frequency.

Considering the way in which they responded to the combined speed-amplitude instructions, the children generally showed sensitivity to the natural inverse relationship between the two parameters. As they grew older the sensitivity became more pronounced. At nine years of age, imposing larger amplitudes elicited lower frequencies and instructing higher frequencies elicited smaller amplitudes, as expected.

Theoretically, the improved performance we presently observed as the children aged between 7 and 9 years might be related to the development of abilities such as transitivity (Piaget & Inhelder, 1965; Pears & Bryant, 1990). The ability to understand the ordinal scaling of elements on the basis of one of their geometrical properties, e.g., length, height etc. - i.e. being able to recognize and apply transitive relations - presupposes an internal representation of such parameters. Here, we presume that our participants have the parameters movement amplitude and frequency internally represented while performing our loop-writing task. In first grade the children's age range was between 6.3 and 7.5, an age in which the possibility of still lingering disorganization between temporal and spatial similarities in movement performance cannot be excluded (see also Vinter et al., 1991).

Next we turn to how quick the children settled into the task as far as meeting the amplitude and frequency constraints concerned. With respect to movement amplitude, the children used the second movement cycle to explore the task requirements and settled into the correct amplitude occurred in the third and fourth movement cycles. Here a clear developmental change was found. Adaptations to the frequency task requirements were comparable. The children again primarily used the second movement cycle to settle into frequency requirements. The developmental trend was less pronounced than observed in the amplitude data. In sum, the first part of our prediction where we assumed that children would be able to settle quickly into task requirements as reflected by decreasing performance errors, was confirmed. The second part in which we predicted improvement with age was only confirmed for the amplitude requirements, and then specifically in the second cycle.

The movement efficiency increases that we did observe as the children aged can be attributed to several factors. First, with age children are likely to develop better sensorimotor representations of learned tasks (e.g., by generating internal models), which in turn allow the central nervous system to comply with the spatiotemporal demands of the task better. Second, attentional capacity should not be ruled out as potential factor. The combination of visual and auditory stimuli in our experimental task may have imposed relatively strong attentional demands on our participants. In their longitudinal study of attentional capacity in 6- to-12-year-old children, Robbers, Van Oort, Polderman, Bartels and Huizink (2011) identified attentional problems in 18% of their subject group. Considering that our participants were typically developing primary school children, a similar percentage could be estimated to have had attentional deficits, a matter that we did not assess separately. Consequently, at age 7 the children might have been particularly prone to fatigue while trying to keep up attention for 45 minutes. This might explain the larger number of error trials observed at this age. A third factor involved might be that the children performed the loop-writing task in a more closed-loop fashion at age 7 whereas at age 9 they may have managed to adopt more open-loop control strategy. In order to determine the extent to which the age-related movement efficiency increase can be attributed to an improved capability to exploit the biomechanics of their developing motor system such as inertia, interaction torques and energy costs, future research should include kinetic analyses and estimate to what extent the motion of the hand is driven by concentric and eccentric muscle contraction. Another approach would be to look into smoothness of acceleration or deceleration profiles, presuming that skilled performers are expected to be less jerky.

Efficiency in cycle-to-cycle parameter changes

Our main prediction was an age-dependent increase in the efficiency with which the children would exploit the inverse amplitude-frequency relationship when correcting movement errors while settling in into our loop-writing task. Even though marginal, we found, contrary to our expectations, an age-dependent *decrease* in this error-correction efficiency. This unexpected result may seem uninformative but in the light of developmental theories, the almost constant efficiency of cyclical movement behavior in an educationally relevant task is in our view remarkable (Harcum, 1990). Indeed, whether motor development between 7 and 9 years of age is linear or non-linear, the observed constancy reflects an inability to increase performance-monitoring efficiency, which in our view must reflect an important constraint on skill acquisition. We will return to this aspect below.

In the present study we found that the incidence of parameter changes that were in line with the inverse amplitude-frequency relationship amounted to 61%. In a study using the same paradigm involving adults, Bosga et al. (2005) reported an incidence of 41% of such parameter changes. This relatively low incidence of this

specific category of parameter changes was probably due to the more stringent timing constraints of the adult task (where 4 and 5 Hz movement frequencies were also tested).

Relation to educational settings

The absence of an efficiency increase in error correction as the children aged between 7 and 9 years might be due to various educational factors. For example, the children may, at this stage of their development, still be occupied with discovering, through trial and error, how fast and accurate they need to be in order to achieve the task goals but not yet actually be able to combine speed and accuracy properly. An alternative cause for our findings might be that as the children grew older, they (i) became eager to show their potential in test situations such as used here, and (ii) the amplitude targets might have been more easily attainable than the frequency targets, e.g. because vision dominates audition (see also below). In case of such bias for spatial processes, the sensitivity to the inverse relationship between the amplitude and frequency might be compromised. In a similar vein, the handwriting curricula in the Netherlands emphasize accuracy of letterform within a prescribed space starting in first grade, with lineation height around 4.5 mm. In second grade speed exercises are added, still within a prescribed lineation height, now of 3.5 mm. In third grade this is maintained, with a lineation size of 2.5 mm., so it is not unthinkable that the children implicitly try to comply with their teachers' wishes. Trap-Porter et al. (1983) found space size and accuracy in 2nd and 3rd graders to be related. Cursive writing is enhanced when large-spaced writing paper is used in these grades. Although the research concerned manuscript writing, a similar result was found for 1st graders by Kau-To Leung, Treblas, Hill and Cooper (1979). In school settings, spatial restrictions are indeed more important in handwriting curricula than temporal constraints (Graham & Weintraub, 1996). As proposed, such emphases on spatial task goals may prevent children from flexibly changing their movement parameters while monitoring and correcting their performance errors. The just described educational factors may also be at odds with sensorimotor developmental processes.

Theories of sensorimotor learning state that the amount of cognitive control diminishes where experience and training increase (Gentile, 2000; Fitts & Posner, 1967). When cognitive control is gradually replaced by automaticity the learner must increase consistency and efficiency until the most economic coordination pattern is reached. An overall increase of biomechanically efficient error correction, as would be expected to accompany reduced cognitive control, was currently not found.

Potentially, because the children had to start the loop-writing task while adjusting to a metronome, thus enforcing an explicitly planned and cognitively controlled action. Clearly at this age children are not yet fully able to efficiently combine auditory, visual and motor information. When older and more experienced in handwriting, eight and nine year-old children are probably more able to use feedforward processes as an anticipatory error-correction mechanism. They are trained to maintain the vertical amplitude of their script between the horizontal lineation and probably are also able to treat auditory and visual stimuli as one compound stimulus, where amplitude requirements are more important than temporal cues. In their study on dissociation of explicit and implicit timing in repetitive tapping and drawing movements, Zelaznik, Spencer and Ivry (2002) concluded that the timing of movement initiation is an explicit process, whereas the timing of movement duration is an implicit process. They further concluded that once the movement is started temporal control might emerge as a function of higher-level conceptualization of the task change to an emergent property of other control processes.

Conclusion

The present study provided a window into adaptation and development using a loop-writing task in which multiple goals needed to be achieved simultaneously. A cohort of primary school children was followed at 7, 8 and 9 years of age with the purpose to record the changes in movement efficiency in childhood. In contrast to our expectations, we observed relative constancy as regards the exploitation of the inverse relationship between amplitude and frequency while correcting parameter errors. The lack of exploiting amplitude-frequency relationships during error correction may be due to the emphasis on spatial accuracy in current handwriting educational practices in the Netherlands, which makes abundant use of lineation combined with global speed instructions. A crucial question that still remains concerns inter-individual differences and, more importantly, the relevance of motor efficiency and flexibility for school performance.

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Chapter 4

Emerging Behavioral Flexibility in Loop Writing: A longitudinal study in Grades 1, 2 and 3 of Primary School

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Emerging Behavioral Flexibility in Loop Writing: A longitudinal study in Grades 1, 2 and 3 of Primary School

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In press. Motor Control

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Abstract

The development of the ability to adapt one's motor performance to the constraints of a movement task was examined in a longitudinal study involving 7-to-9-year-old children who were asked to perform a preparatory handwriting task. The capacity for sensorimotor synchronization was captured by the standard deviation of the relative phase between pacing signals and writing movements and the capacity to adjust wrist-finger coordination while performing repetitive movements was analyzed by autocorrelations of the vertical pen-tip displacements. While the capacity for synchronization improved with age, the autocorrelations were positive at short time lags only and hardly changed with age. A measure of 'the long-term memory' of time series (Hurst exponent) confirmed that the findings were systematic rather than noise. Collectively, the results indicate that flexible movement strategies emerge early on in the first three years of formal handwriting education. Implications for educational and clinical practice are considered.

Introduction

In the first three years of primary school the skill of handwriting is formally being trained. During that critical period 7-to-9-year-old children in The Netherlands have to learn to execute in parallel the language and motor processes that together make up handwriting. The language skills - also labeled literacy skills - concern all sub skills involved in reading and writing, namely awareness of speech sounds (phonology), knowledge of the relationships between sounds and letters and letter representations (i.e., phoneme-grapheme matching skills and allograph knowledge), spelling skills (orthography), knowledge about grammatical rules, and, finally, representations of word meaning (semantics) (Tolchinsky, 2006; Van Galen, 1991). As regards motor processes, the spatial and temporal requirements to generate recognizable letter shapes through pen-tip movements have to be mastered. The gradual automatization of this complex system of language and motor skills is imperative for the ability to produce legible handwriting within an acceptable timespan. Obviously this process is not a trivial matter considering the many components that are involved in learning the handwriting skill. Indeed, manipulating a writing tool to generate even a single target letter at various positions in the graphic workspace is highly complicated when considering the changing conditions under which such a task takes place (Latash, Danion, Scholz, Zatsiorsky, & Schoner, 2003; Newell, 1986; Thelen, 2005; Vaillancourt, Sosnof, & Newell, 2004). For example, writing a simple grapheme 'e' at the beginning of a sentence in the left area on a writing line on a piece of paper requires a different wrist-finger coordination than writing the same grapheme at the end of that writing line close to the right-hand side of the paper (Thomassen, Meulenbroek, Schillings, & Steenbergen, 1996). Thomassen et al. asked participants to produce 12 to 18 letter-sequences ('e' of 'n') sequences to study wrist-finger coordination at various positions on the line of writing. They observed considerable changes in wrist-finger coordination at the left, middle and right part of the line of writing. Such delicate changes in movement coordination, but now at the level of temporal consistency of performance, are the subject matter of the present longitudinal study. In the present study we scrutinize the ability of 7-to-9 year-old primary school children to perform a specific preparatory handwriting task, viz., producing loops resembling the letter '*e*'. We chose this letter-like writing task to avoid any letter-complexity effects. The ability to adapt wrist-finger coordination while writing a continuous series of the letter '*e*' is considered here as a solid way to assess behavioral flexibility because in order to maintain acceptable levels of spatial invariant output people have to flexibly adapt their movements to continuously changing temporal and spatial constraints (Meulenbroek, Rosenbaum, Loukopoulos, Thomassen, & Vaughan, 1996; Zanone & Athènes, 2013). This also holds for handwriting acquisition and one way of capturing behavioral flexibility is through a refined analysis of movement variability.

Early views on movement variability in handwriting emphasize the underlying mechanism of neuromotor noise, where low endpoint variability is interpreted as skilled performance (Newell, Deutsch, Sosnoff, & Mayer-Kress, 2006; Van Galen & Huygevoort, 2000; Van Galen, Portier, Smits-Engelsman, & Schomaker, 1993). A decrease in intraindividual variability with increasing age reflects an improvement in consistency of performance. More recently, this one-dimensional view on movement variability has been claimed to be too narrow and attention shifted to long-term temporal dependencies in movement variability, where an increased variability is taken to reflect an increased capacity to use more flexible strategies (Adolph, Cole, & Vereijken, 2014; Longstaff & Heath, 1999; Stergiou, Harbourne, & Cavanaugh, 2006; Torre & Balasubramaniam, 2011). Dedicated time-series analysis tools to quantify the time-varying changes in behavioral flexibility have recently been explored in a variety of motor tasks ranging from sitting to standing and walking (e.g.: Harbourne & Stergiou, 2003; Hunt, McGrath, & Stergiou, 2014; Lamoth, Van Lummel, & Beek, 2009). Practically, this view regards intrinsic variability as a different entity than end-point variability and other performance-variability measurements. Here, variability is seen as a time-varying exploration of many possible solutions of a movement task. Relatedly, development is described as a "process of assembling patterns of behavior to meet demands of the task in the biological possibilities of the child at that time" (Thelen, 2005, p. 263). Intrinsic variability is thus viewed as a substantial feature of a non-linear, stochastic or a noisy system, which reflects how people learn the best solution to solve a motor task and attain stable performance. Consequently, patterns of change over longer periods of time as revealed in long-range dependencies in cyclical movement tasks became a matter of interest in behavioral studies (Adolph et al., 2014; Torre & Balasubramaniam, 2011).

In earlier research we developed a simple handwriting task in which children were asked to perform spatially constrained and acoustically paced preparatory writing movements (sequences of the letter '*e*') to systematically challenge the children's perceptive, temporal and spatial capacities, while eliminating reading and spelling demands. We focused on the development of cycle-to-cycle movement-error correction strategies of children in the first three years of formal handwriting education and found an age-dependent increase in accurate reproduction of the combined spatial and temporal targets of the task (Bosga-Stork, Bosga, & Meulenbroek, 2014). In our earlier study we assumed that children, over the years, would increase their ability to exploit the inverse relationship between amplitude and frequency while correcting movement errors. Marginal increases in exploiting amplitude-frequency relations in error correction were found, leaving the question of how behavioural flexibility changed as function of time unanswered. In the current study we extend our research to scrutinize the short and long-term flexibility in performance beyond the cycle-to-cycle changes in our repetitive movement task.

In the present study we reanalyze our earlier obtained data (Bosga-Stork et al., 2014) paying particular attention to the development of behavioral flexibility as children (7, 8 and 9 years old) learn to master handwriting in Grades 1, 2 and 3 in Dutch primary school. Following Hollerbach (1981, see also Singer & Tishby, 1994), the preparatory writing task we used can be seen resulting from coupled oscillations in horizontal and vertical directions, which together produce letter-like forms. We apply time-series analysis i.e. comparisons of repeatedly produced movements within a sufficiently long time interval during which the behaviour is digitized at a high rate. The comparisons concerned, among other measures, correlations.

We focus on age-related changes in the autocorrelations and the Hurst exponent (Jebb et al., 2015; Rosenblum & Roman, 2009). The autocorrelations can be seen as a spectrum, where weaker correlations reflect less time-dependent self-similarity in the movement patterns, which is taken to indicate behavioral flexibility. Weaker short-term autocorrelations of cyclically performed movements mean that at a particular moment in time the ongoing behavior is less influenced by past behavior and this past and ongoing behavior is thus less likely to influence future behavior. In contrast, stronger autocorrelations reflect greater time dependent self-similarity in the movement patterns, which is taken to reflect behavioral rigidity, i.e., earlier behavior is more likely to determine present and future behavior. Suppose, theoretically, that if the autocorrelations diminish to zero in the course of the time series, present and future behavior is not determined by information in the past. In contrast, if the autocorrelations approximate +1, present and future behavior is completely determined on information in the past.

Similarly, a relative small Hurst exponent is assumed to reflect behavioral flexibility in loop writing over time and relative larger values indicate more behavioral rigid loop writing performance. Moreover, absolute Hurst exponent values larger that 0.5 provide assurance that the time series under analysis are not merely time independent time series i.e. random noise (Ihlen, 2012; Rosenblum & Roman, 2009).

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To estimate the produced rigidity of the oscillations of the loop writing performance, we captured the synchronization capacity of the children by assessing the phase relationship between the sinusoidal pacing signal and oscillating vertical pen-tip translations as expressed in the standard deviations of the continuous relative phase signals as a measure of coordination variability.

Earlier studies (Drake, Jones, & Baruch, 2000; Drewing, Aschersleben, & Li, 2006; Volman & Geuze, 2000) have demonstrated that the stability of movement coordination patterns in cyclical, i.e. continuous, tasks increase as a function of age. In the present study we expected this to be reflected in an age-dependent decrease of the standard deviation of relative phase. As children grow older and become more experienced in motor tasks, they will be more capable of flexibly adapting their performance to environmental and task constraints (Badaly & Adolph, 2008; Bosga-Stork et al., 2014; Gentile, 2000; Mergl, Tigges, Schröter, Möller, & Hegel, 1999; Meulenbroek & Van Galen, 1986). Furthermore, Rosenblum and Roman (2009) observed in their experimental study on fluctuations in the handwriting speed of proficient and dysgraphic handwriting in school children, that strong short-term autocorrelations (within a single character or letter) characterize proficient handwriting. Long-term autocorrelations tended to be low. For our longitudinal study of the development of flexibility in handwriting between 7 and 9 years of age, we expected the short-term autocorrelations to increase with age and the long-term autocorrelations and the long-term memory of the time-series (i.e., the Hurst exponent) to decrease with age.

Methods

Participants

A group of 32 children (fifteen girls and seventeen boys, mean age 7;1 (years; months); range 6;4 - 7;6 in grade 1) was investigated during 1st, 2nd and 3rd grade of primary school. All participants were of Caucasian race and had the Dutch language as their first language and had normal hearing and normal or corrected-to-normal vision. Four girls and two boys were left-handed. None of these children repeated a grade. The primary school's institutional review board approved of the study and the school principal supported the research and each year the parents of the participants gave their informed consent and all children agreed to participate. Each child received a little present after each experiment. Experimental procedures followed the APA guidelines for the ethical treatment of human participants.

Procedure and Materials

The children were tested individually in a quiet room in the school, seated on a height-adjustable chair, with their feet supported and in a writing position adapted to the height of the digitizer tablet. The children were required to write loop patterns with an electronic pen (Intuos3) on preprinted sheets of paper attached to a digitizer tablet (WACOM A4 Oversize tablet) paced by a sinusoidal modulated acoustic signal. The pacing signals' intensity varied across a clearly audible range (approximately 60-70 dB; tone pitch 330 Hz). The loop pattern's height was 3, 6, 9, or 12 mm; the acoustical pacing was 1, 2, or 3 Hz. The 12 preprinted trial sheets consisted of six repetitions (block) of the twelve amplitude-frequency combinations, which were presented at random (see Figure 1).

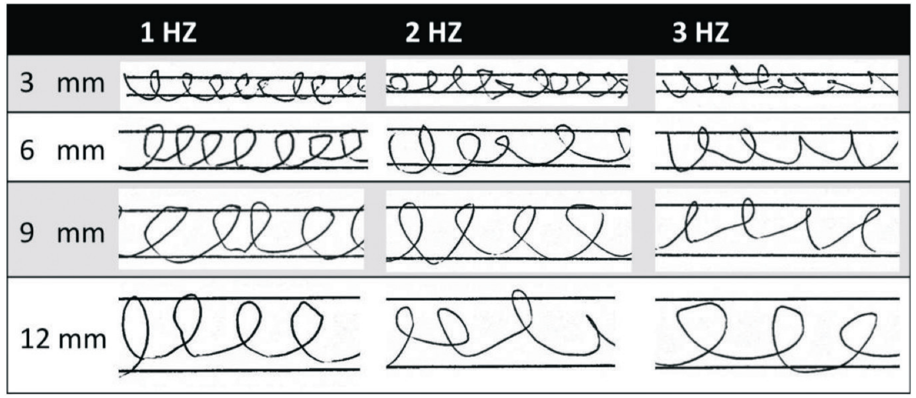

Figure 1. *Twelve samples of produced loop-writing patterns by an 8-year-old male pupil. The four pattern heights (3, 6, 9 and 12 mm) were generated in the 1, 2 and 3 Hz pacing conditions, separately. Each child produced six repetitions (blocks) of the twelve amplitude- frequency combinations: in total 72 patterns of 18 loops each. They wrote on preprinted sheets of paper (A4) fixed on a digitizing tablet, using an inking pen.*

Frequency-amplitude combinations did not vary within blocks. The experimental session consisted of a total of 72 trials of 18 loops, leading to a theoretical total of 1296 loops per experiment at age 7, 8 and 9 (i.e. a maximum of 3888 loops per child). The first author administrated the loop-writing task in March each year. Before the experiment started all children were shown how to combine the loop writing and pacing sounds. The children in Grade 1 were allowed to perform two repetitions of the 9 and 12 mm pattern-height conditions using the three different acoustical signals (12 practice trials) to get comfortable with experimental procedures and task requirements. In Grades 2 and 3 each of the three frequencies was practiced twice, using only the 9 mm loop pattern (6 practice trials) since all children remembered what the procedure was. No further instruction was given during the test, which took around 45 minutes and was performed without pause.

Data analysis

On-line recordings of X, Y and Z (axial pen force) were sampled at 200 Hz (Bosga- Stork, Bosga, & Meulenbroek, 2011). For the successive measures we only used the vertical pen-tip displacements that were subsequently subjected to a linear interpolation of missing data points. Preprocessing of the vertical pen-tip displacements for the performed amplitude and frequency and the standard deviation of the relative phase involved a 2nd- order, zero phase-lag Butterworth filtering with a cut-off frequency of 8 Hz and detrending. To avoid artefacts due to smoothing by means of the Butterworth digital filter, we excluded the first and last cycle of each trial after the filtering.

Loop writing measures

Amplitude and frequency performance

The performed amplitude and frequency reflect the accuracy and efficiency the children attain in reproducing the instructed spatial and temporal targets imposed by the task. By means of an automatic peak-detection algorithm and the extrema in the vertical pen-tip displacement data the performed amplitudes and frequencies were found. The automatic detection of extrema was visually checked to ensure that extrema and peak- detection coincided. A total of 1.78% of the trials (n = 419) did not comply with the aforementioned criterion and were rejected. Subsequently, the mean amplitude and frequency performance were calculated (see for extensive description Bosga-Stork, Bosga & Meulenbroek, 2011).

Standard deviation of the relative phase

Continuous relative-phase time functions were inspected for branch cut crossings (phase wraps). No branch cut crossings were found. The standard deviations (SDrph) of the continuous relative-phase signals of the vertical pen-tip displacements and the acoustic pacing signal were calculated using Batschelet's (1981) procedure for circular statistics (see Meulenbroek et al., 1998). The standard deviation of the relative phase provides information about the strength of the coupling between the vertical pen-tip displacements and the acoustic pacing signal.

Autocorrelation

Preprocessing of the autocorrelation measurements (r) and the Hurst exponent (H) involved resampling of the vertical pen-tip displacement data to 100 Hz, detrending procedures and, because we used unfiltered data, inclusion of the first and last cycle of each trial in the analysis. Autocorrelations (Pearson product-moment) are used to detect serial dependency in data and describe whether a variable is correlated with itself across different time points. Autocorrelations disclose information about the effect of the current state on the next state in time series. In this study we applied the autocorrelation function of the vertical pen-tip displacements with shifted (lagged) copies of itself as a function of a lag size. The time lag size for the autocorrelation measures was N/7 in which N was the number of data points per trial, thus dividing the trial into seven segments consisting of N/7 data points each. Next, the maximum of the Pearson product-moment between all data points of the first segment (S1) and a sliding window across the full range of data points of the second (S2) and third segment (S3) was determined (S2+1:S3+1) and denoted Time lag 1. For the long- term autocorrelations this procedure was repeated between segments S1 and S3+1:S4+1, S1 and S4+1:S5+1, S1 and S5+1:S6+1, and S1 and S6+1:S7+1 for all trials and subsequently denoted as Time lag 2, 3, 4 and 5. For the short-term autocorrelations the above procedure was repeated between segments S2 and S3+1:S4+1, S3 and S4+1:S5+1, S4 and S5+1:S6+1 and S5 and S6+1:S7+1 for all trials and subsequently denoted as Time lag 2, 3, 4 and 5. The maximum of the Pearson product-moment was then converted to a normally distributed variable by means of the Fisher's z' transformation.

Hurst exponent

The Hurst exponent (H) relates to the autocorrelations of the time series, and to the rate at which the autocorrelations decrease as the lag between pairs of values increases. It is one of several scaling exponents used to parametrisize the multifractal structure of time series. Its range defines the continuum of fractal structures between 0-1.5, in which a H in the range 0 - 0.5 means that a single high value in the time series will probably be followed by a low value and visa versa, white noise (H=0.5) signifies completely uncorrelated or time independent time series i.e. random noise, a value H in the range 0.5-1 indicates a time series with long-term positive autocorrelations (Ihlen, 2012) and Brown noise (H=1.5) signifies slow evolving fluctuations. In this study we followed the procedure to determine the Hurst exponent as described in Ihlen's Introduction to multifractal detrended fluctuation analysis in Matlab (2012).

Statistical analyses

Statistical analyses consisted of separate repeated measures analyses of the two dependent measures (SD relative phase, Hurst exponent) according to a 3 Age (7, 8, 9) x Imposed Frequency (1, 2, 3 Hz) factorial design. A third and fourth repeated measures analysis was conducted on the long-term and short-term Fisher's z' transformed maximum of the Pearson product-moment according to a 3 Age (7, 8, 9) x 5 Time lag (1, 2, 3, 4, 5) factorial design.

Results

The general performance of the children quantified as the difference between instructed and realized amplitudes and frequencies in ages 7, 8 and 9 is shown in Table 1.

Table 1. *Means and standard deviations of the realized amplitudes and frequencies as function of the instructed amplitudes and frequencies.*

		Age		
		7	8	9
		Realized Amplitude		
Factor	Level	Mean [SD]	Mean [SD]	Mean [SD]
Instructed Amplitude	3 mm	3.67 [1.01]	3.46 [0.66]	3.36 [0.59]
	6 mm	5.66 [1.01]	5.53 [0.92]	5.51 [0.73]
	9 mm	7.57 [1.45]	7.72 [1.40]	7.64 [1.25]
	12 mm	9.43 [1.81]	10.03 [1.66]	9.78 [1.69]
		Realized Frequency		
Instructed Frequency	1 Hz	1.13 [0.17]	1.12 [0.14]	1.11 [0.16]
	2 Hz	1.90 [0.28]	1.95 [0.26]	2.01 [0.23]
	3 Hz	2.40 [0.55]	2.65 [0.48]	2.74 [0.41]

Overall the children produced the instructed amplitudes adequately. In all grades the children showed an overshoot in realizing the instructed amplitude of 3 mm, while realizing undershoots for 6, 9 and 12 mm. As far as the realized frequencies are concerned, the children also complied with the task instructions. At all ages the children produced small overshoots for the instructed frequency of 1 Hz and small undershoots for 2 and 3 Hz. Growing efficiency was shown by the increase in performance accuracy, as the children grew older.

Figure 2 (left panel) shows the standard deviation of the relative phase (SDrph, degrees) as a function of Age and Instructed Frequency. The developmental trend showed that at 7 years of age, just learning to write, children are less able to synchronize writing performance and auditive stimuli, but improve with age. The main effects for Age and Instructed Frequency were statistically significant, $F(2,62) = 20.082$, $p = < .001$ and $F(2,62) = 14.334$, $p = <. 001$, respectively. The interaction was statistically not significant, $F(4,124) <1$, *ns.*

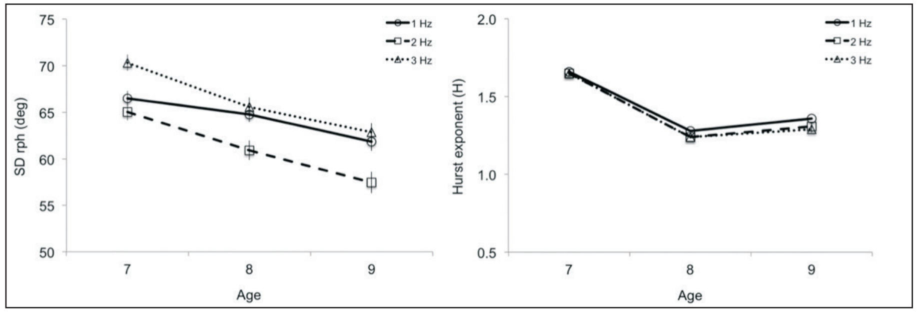

Figure 2. *Left panel: standard deviation of the relative phase in degrees (SDrph), and Right panel: the Hurst exponent as a function of the instructed frequency of 1, 2 and 3 Hz and at Ages 7, 8 and 9 years*

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Figure 2 (right panel) presents the Hurst exponent as a function of Age and Instructed Frequency. The results showed overall values for H = > 1.0, showing that the vertical pen-tip kinematics can be characterized as slow evolving fluctuations. The main effect of Age was statistically significant, $F(2,62) = 110.360$, $p <.001$. Mauchly's test indicated that the assumption of sphericity for the main effect of Instructed Frequency had been violated, $\chi2(2) =23.502$, $p < .05$, therefore a Greenhouse-Geisser ($\varepsilon = .65$) correction was used. The results showed that the Hurst exponent was statistically significant affected by Frequency, V = 0.83, $F(2,30) = 74.346$, $p <. 001$, Partial $\eta2= .79$. Mauchly's test indicated that the assumption of sphericity for the interaction between Age and Instructed Frequency had been violated, $\chi2(9) =29.731$, $p < .05$, therefore the Greenhouse-Geisser ($\varepsilon=.72$) correction was used also. The results showed that there was a statistically significant effect of the interaction, V=0.61, $F(4,28) = 11.065$, $p < .001$, Partial $\eta2 = .56$.

The long-term autocorrelations (LTAC) of the trials, as a function of the Time lag and Age are shown in Figure 3, left panel. The results showed that the LTAC were on average weakly correlated ($r = 0.38$) displaying a decreasing and statistical significant developmental viz. for Age 7 (r = 0.42), Age 8 (r = 0.37) and Age 9 (r = 0.35). Mauchly's test indicated that the assumption of sphericity for the main effect of Age, the main effect of Time lag and the interactions of Age and Time lag had been violated. For the main effect of Age: $\chi 2(2) = 8.108$, $p < .05$, a Greenhouse-Geisser (ε = .81) correction was used. The result shows that the LTAC were statistically significant affected by Age, V = 0.67, $F(2,30) = 30.446$, $p < .001$, Partial $\eta 2 = .66$. For the main effect for Time lag: $\chi 2(9) = 180.957$, $p < .05$, a Greenhouse-Geisser (ε=.29) correction was used. The result showed that LTAC were statistically significant affected by the Time lag, V = 0.84, $F(4,28) = 38.176$, $p < .001$, Partial $\eta 2$= .69. For the interaction effect: $\chi 2(35) = 229.474$, $p < .05$, a Greenhouse-Geisser (ε = .28) correction was used. The result shows that the LTAC was not statistically significantly affected by the interaction of Age and Time lag size, V = 0.40, $F(8,24) = 2.016$, p = *ns* (p = .088), Partial $\eta 2$ = .020.

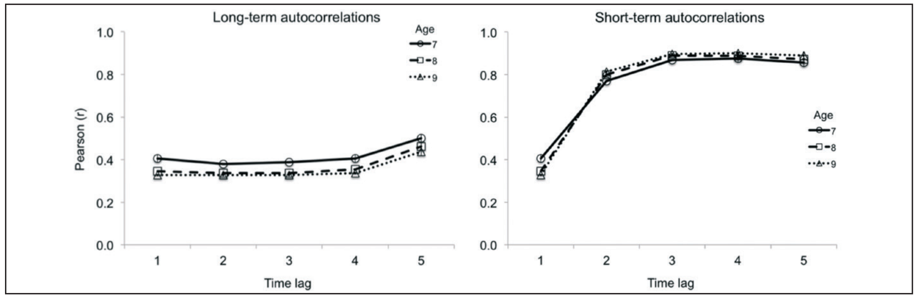

Figure 3. *Long-term (left panel) and short-term (right panel) autocorrelations for the trials over the Ages (7,8 and 9). Time lag 1, 2, 3, 4, 5 for the long-term autocorrelations (left panel) correspond to the autocorrelations between segments S1 and S2+1:S3+1; S1 and S3+1:S4+1, S1 and S4+1:S5+1, S1 and S5+1:S6+1; S1 and S6+1:S7+1 whereas time lag 1, 2, 3, 4, 5 for the short-term autocorrelations (right panel) correspond to the autocorrelations between segments S1 and S2+1:S3+1; S2 and S3+1:S4+1, S3 and S4+1:S5+1, S4 and S5+1:S6+1; S5 and S6+1:S7+1.*

The short-term autocorrelations (STAC) as a function of Time lag and Age are shown in Figure 3, right panel. The result showed that the STAC were on average strongly correlated (r = 0.81) displaying an increasing trend viz. for Age7 (r = 0.79), Age 8 (r = 0.81) and Age 9 (r = 0.82). STAC of the trials as a function of Time lag and Age are shown in Figure 3B. The main effect of Age was statistically significant, $F(2,62) = 15.525$, $p < .001$. Mauchly's test indicated that the assumption of sphericity for the Time lag and the interaction of Age and Time lag had been violated; The main effect of Time lag: $\chi 2(9) = 94.388$, $p < .05$, a Greenhouse-Geisser (ε = .40) correction was used. The result shows that STAC were statistically significant affected by the Time lag, V = 0.98, $F(4,28) = 361.612$, $p < .001$, Partial $\eta 2$ = .98. For the interaction effect: $\chi 2(35) = 72.995$, $p < .05$, a Greenhouse-Geisser (ε = .61) correction was used. The result showed that the STAC were statistically significant affected by the interaction of Age and Time lag size, V = 0.74, $F(8,24) = 8.382$, $p <. 001$, Partial $\eta 2$ .74.

Discussion

Childhood is a period of remarkable changes in cognitive and motor competence. Learning to write is an ongoing process of trying to find adaptive strategies to close the gap between the linguistic targets and the actually performed movements. A legible handwriting performance reflects sufficient consistency with enough behavioral flexibility to cope with continuously changing task demands. To broaden the view of the development of movement variability in handwriting that is often limited to the assumption that less variability in execution is more skilled performance, we explored in a graphomotor '*e*' writing task (consisting of continuous loops), how movement variability modulates over time. Together with the standard deviation of the relative phase, which captures the children's capacity for sensorimotor synchronization, the autocorrelations and the Hurst exponent of the '*e*'- writing task as measures of time-dependent self-similarity of the movement kinematics were assessed over two years of development, at 7, 8 and 9 years of age.

The choice for an acoustical, temporally paced, closed-loop task of spatially defined letter-like movements prompted the participating children to synchronize their movements adequately to the presented sensory information (Drewing et al., 2006; Repp & Su, 2013; Volman & Geuze, 2000). Getchell (2007) showed that auditory pacing improves intrapersonal temporal coordination in walking and clapping, expressed in an increase of consistency of sensorimotor synchronization, as children grow older. Our cohort of children was also capable to match the vertical pen-tip movements to the acoustic pacing signal better, as they grew older. That is, as beginning writers at the age of 7, the children were less able to cope with a combination of visually controlled motor output and auditive stimuli, with age the capacity to couple motor response to a sensory stimulus resulted in a more consistent adapted performance. In the literature, a linearly increasing trend towards a more stable sensorimotor synchronization is reported to take place between 5 and 12 years of age (Kotz et al., 2014; Repp, 2005; Repp & Su, 2013; Wing, Doumas, & Welchman, 2010; Volman & Geuze, 2000), which is in keeping with our results that show a decrease in coordination variability albeit behavioral flexibility for the development over 6 years and 4 months to 10 years and 7 months age range. Even though coordination variability decreased with age, the overall value of ~ 61 degrees for 9 year olds indicates that the sensorimotor synchronization cannot be assessed as rigid. Although the coupling response improved over the grades, in our study the growing consistency in sensorimotor synchronization was more explicit for the 2 Hz frequencies than for the 1 and 3 Hz frequencies. Kurgansky (2011) observed that the range for a successful synchronization of seven- and eight-year- olds is rather narrow, from 600 - 700 ms, which is agreement with the 2 Hz frequencies in our study, and this observation we can now extend to nine-year-olds. The children themselves also declared the 2 Hz frequencies to be the preferred tempo for all three years of handwriting development. In conclusion, repeated performances of the letter-like loops ('*e*') revealed that children improved in matching their pen-tip movements to the pacing signal over the three years of development studied but that overall coordination variability remained relative flexible. Variability in task performance, albeit within a certain range, is seen as indicative of adaptive and flexible behavior, responding to individual constraints in the context of task conditions. Absence of variability in this context is seen as a form of rigidity (Adolph et al., 2015). We therefore looked into developmental change in the structure of variability as expressed by long-term and short-term dependencies in time series.

In general, long-term (LTAC) and short-term (STAC) dependencies in time series reflect the degree in which present and future behavior is more likely to depend on earlier behavior.

In our research, long-term dependencies in time series displayed on average an autocorrelation value of ~0.38 with a SD of ~0.09 (see figure 3, left panel). This means that performance at the start of the trial was of moderate but consistent influence on the remaining part of the trial. We take this to be indicative of the lingering influence of cognitive preparation on movement execution during the trial. Globally, at the Ages 7, 8 and 9 the children displayed comparable features of long-range self-similarity in the time series. However, in comparison to the ages 8 and 9, seven year olds showed slightly stronger autocorrelations, expressing more time-dependent self-similarity in movement execution. These observations could imply an increased of behavioral flexibility, as children grow older. Anticipating on the task requirements, i.e. the end of the trial, the children showed stronger LTAC in all grades probably reflecting relatively slow visuomotoric control, consistent with the task requirements. The Hurst exponent underlines the increase in behavioral flexibility over the years, since for 7 year olds the Hurst exponent was larger than for the 8 and 9 year olds. In their research Rosenblum and Roman (2009) also, for their group of proficient hand writers, found similar uncorrelated behavior over longer periods.

The short-term dependencies in time series displayed on average an autocorrelation value of ~0.81 with a SD of ~0.40 (see figure 3, right panel). This means that, in contrast to long-term dependencies, behavioral information of the recent past is highly relevant for present and near future. Because short-term time-dependent self-similarity is relatively high, we presume that these observations globally represent behavior in which ongoing movement adaptations are increasingly informative for near future movement execution. We consider these results a hallmark of behavioral flexibility to cope with continuously changing task demands. Our supposition is underpinned by observations that in comparison to 7-years-olds, 8- and 9-year-old children showed, on average, slightly stronger autocorrelations, expressing that ongoing movement changes are more informative for near future movement execution. Taken together, the results of the long- and short-term autocorrelations show that movement preparation, at the age of 7 as opposed to ages 8 and 9, determines to a larger extent movement behavior in the course of the trial whilst adaptive changes are less influential in the near future.

Our results are comparable to fluctuation analysis in handwriting by Rosenblum and Roman (2009). Using Hebrew characters (right to left) as a handwriting task, they found proficient handwriting to be characterized by strong short-term autocorrelations (within a character in their study) and more uncorrelated long-term autocorrelations. The replication of general results concerning proficient handwriting in a group of developing hand writers, using different tasks and different analyses substantiate both studies.

Even though handwriting is a complex task for which more parameters have to be taken into account, the combination of measures of performance, movement errors, coupling strength of perception and actions and finally (non) identical movement patterns in time-series, may be crucial for decisions on interventions targeted at facilitating the motor aspects of handwriting development. In our view, this is a promising educational and/or clinical approach since it is in these contexts that teachers and clinicians are in need of quantifying the adaptive capabilities of an individual at various time scales, including development. Although a simple letter like loop-writing task is informative for handwriting assessment, technical constraints to use nonlinear tools are still in place in daily practice. The next step will be the introduction of the concepts of flexibility in handwriting assessment and the experimental use of accelerometers during simple handwriting tasks, while finding a way to make analyses accessible and interpretable in a broader clinical setting.

Our study fits in with the increasing number of studies on developmental variability that help us to understand the developing control strategies used by children (e.g. Harbourne & Stergiou, 2003, 2009; Deffeyes, Harbourne, Kyvelidou, Stuberg, & Stergiou, 2009). In general, all studies report variability in motor strategies in response to changing task conditions, which happens to satisfy both ends of the spectrum used when measuring successful performance: sufficient consistency while maintaining flexibility needed to adapt to changing circumstances.

Conclusion

The development of the ability to repeatedly adapt one's motor performance to the changing demands of a movement task, or, as Bernstein stated "repetition without repetition", gives a broader view on the underlying motor capacity of a child. Flexible movements strategies emerge in the first three years of formal handwriting instruction. Adaptive changes in the near future (short-term autocorrelations) are more influential in experienced hand writers at 8 and 9 years of age than in 7-year olds. Applying a time series measure such as autocorrelation not only adds a new dimension to research but also has significant practical implications. For diagnostic and remedial purposes, the use of time-series measures to explore temporal variability adds to the possibility to investigate the variability of a developing motor system by quantifying the performance as it unfolds in time. In future research such a regularity statistic of repetitive movements might contribute to improving our understanding of age-related changes in handwriting fluency measured in tasks that go beyond the basic task of loop (letter '*e*') writing investigated presently.

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Chapter 5

Developing Interactions Between Language and Motor Skills in the First three Years of Formal Handwriting Education

CHAPTER 5

Developing Interactions Between Language and Motor Skills in the First three Years of Formal Handwriting Education

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Abstract

Aims: The present study was designed to provide a basis for teachers and therapists to better understand primary school children's handwriting problems in the face of the complex relationships that exist between literacy skills with the goal to contribute to treatment choices.

Study Design: A longitudinal, experimental study of handwriting-, literacy- and motor skill development of primary school children.

Place and Duration of Study: Two parallel classrooms of a mainstream medium-sized primary school in the Netherlands participated, covering the first three years of handwriting education.

Methodology: General performances and intercorrelations between developing spelling, reading and handwriting skills were assessed for 32 children (15 girls and 17 boys). A standardized handwriting assessment scale was used to measure handwriting speed performance, a nonlinguistic loop-writing task, using an electronic inking pen and a digitizer evaluated motor performance. Reading- and spelling performance was extracted from a national, school-base follow-up system, used by teachers.

Results: At group level the results showed an increase in performance for all measures, the performance of the children showed considerable variation. Spelling and reading were positively related within all grades (p = .004, .0001, and .005 respectively). Handwriting and reading were positively related within Grade 1 only (p = .003), handwriting and spelling were positively related in Grades 1 and 2 (p = .004 and .001 respectively). The amplitude errors in loop writing were negatively related to both language measures in Grade 1 (for reading p = .007, for spelling p = .004).

Conclusion: To broaden the view on developing handwriting problems in individual primary school children, it is advised to assess spelling and reading skills as well as motor skills, especially in the second and third grade.

Introduction

Handwriting is a complex skill, the mastering of which requires several years of formal instruction. About 6 - 27 % of typically developing children are reported to experience serious problems in handwriting acquisition, where the incidence reported depends on the assessment choices concerning grade and methods (Feder & Majnemer, 2007; Hamstra-Bletz, 1993; Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011; Smits-Engelsman, Niemeijer, & Van Galen, 2001; Smits-Engelsman, Van Galen, & Michels, 1995). The results of handwriting education, usually offered in the first three year of primary school, depend, among other matters, upon the proper and timely development and integration of perceptual, language, and motor capacities (Abbott, Berninger, & Fayol, 2010; Berninger, 2000; Berninger, et al., 2006; Berninger, Fuller, & Whitaker, 1996; Childress, 2011; Flower & Hayes, 1981, James & Gaultier, 2006; Jones & Christensen, 1999; Rijlaarsdam, & Van den Bergh, 2006), but each of these cognitive functions is known to develop at its specific rate and with substantial interindividual differences. For example, the perceptual skills of distinguishing and linking sounds to symbols develop at an earlier age than the fine motor skills that produce them (Berninger et al, 2006; Tolchinsky, 2006). Also when starting school, stages of maturity differ and not every child is endowed with the same talent and experience (Karlsdottir & Stefansson, 2002). To provide primary school teachers and therapists with knowledge to help recognize and understand poor handwriting development in the face of the complexity of literacy skills developing at a different rate, more insight into the relationship between these skills in primary school children is needed. Over the years several models have been proposed to describe handwriting processes in relation to other literacy skills. Research based on the educational models of handwriting and writing development has highlighted the importance of the underlying cognitive processes. These models matured against a background of educational research (Abbott et al, 2010; Berninger et al, 1996, Flower & Hayes, 1981; Juel, Griffith, & Gough, 1986; Rijlaarsdam & Van den Bergh, 2006). Juel, Griffith and Gough's 'Simple View' of reading and writing (1986) was based on a longitudinal study showing that spelling was the most important factor that defined writing performance in first grade. In 2000, Berninger extended the 'Simple View' towards a model of four functional language systems (language by hand, by ear, mouth and by eye) that develop independently, but are interconnected. Here, handwriting and spelling are seen as 'lower-level' transcription skills, whereas text generation and executive functions are considered 'higher-level' cognitive skills (Berninger, 2000; Berninger, Yates, Cartwright, Rutberg, & Abbott, 1992).

As in Juel's 'Simple View', letter and word production are most important in the early stages of handwriting development, until these processes become automated. A related model is the psycholinguistic model of handwriting by Van Galen (1991), which differentiated several processes involved in handwriting, each process working on a different time scale (activations of intentions, semantic retrieval, syntactical construction, spelling, allograph selection, size control, and muscular adjustment). As opposed to the models by Berninger and Juel, the model by Van Galen, which is most refined in differentiating processes involved in handwriting, has not been applied to handwriting development. Cross-sectional research (Graham, Berninger, Weintraub, & Schafer, 1998) indicated that handwriting speed increased over the grades. In their longitudinal study Karlsdottir and Stefansson (2002) proposed that dysfunction of handwriting speed (4% of their research group) could be explained as a dysfunction due to handwriting quality, while in their longitudinal study, Hamstra-Bletz and Blöte (1990) found a strong relation for speed and grade. These studies did not take other literacy skills into account. Taken together, the models and studies suggest that the development of handwriting skill in children aged 7 to 9 primarily depends on the gradual automatization of "lower-level" fine motor, spelling and reading skills. Only when attained to a sufficient level, this generates capacity for mental processes at the higher levels of finding words, phrases and meanings (Bourdin & Fayol, 2000; Van Galen, 1991).

The aim of the present study was to widen the perspective on handwriting skill development in relation to the development of literacy and motor skills in Grades 1, 2 and 3. To this end we designed an exploratory, longitudinal study of handwriting acquisition in which we studied the developing relations between literacy and fine-motor skills during the first three years of primary school. In order to combine educational progress in reading and writing with motor related handwriting tasks, an existing school-based tracking system for literacy and a known handwriting assessment task were used. Furthermore, we introduced a fine-motor loop-writing task that put pressure on children's capacities to combine spatial and temporal skills that are expected of children in order to write legibly as well as fast enough. Adopting a longitudinal approach highlighted development. Whereas the majority of studies on handwriting acquisition have used cross-sectional designs, the present study concerned 32 primary school children who were first assessed in Grade 1, and then re- examined in Grades 2 and 3.

Our study addressed three questions. The first question concerned the children's language, handwriting and fine-motor loop-writing performance levels in the first three years of primary school. Which performance levels did our participants attain in Grades 1, 2 and 3? The answer to the first question provided the baseline against which questions concerning developing skill interactions could be formulated. The second question concerned the developing relations between language, fine motor skills and handwriting acquisition. Do spelling, reading and loop-writing skills contribute to handwriting acquisition similarly in each grade or are certain combinations stronger in one grade than in another grade? The final explorative question was whether assessments of handwriting performance, reading skills, and fine-motor skills contribute to our understanding of handwriting problems.

Method

Participants

At the start of the research, all children belonged to two parallel classes of the first grade of a mainstream medium-sized primary school in the center of the Netherlands. Of the 34 children in Grade 1, two children left school at the end of Grade 1 and could not be assessed further due to leaving the school. The remaining 32 children (15 girls and 17 boys) were all evaluated three times (first, second and third grade) for all measures. Their mean age was 7;1 (years; months) in Grade 1 (range 6;4 - 7;6), 8;1 (7;4 - 8;6) in Grade 2 and 9;1 (8;4 - 9;6) in Grade 3. Four girls and two boys were left-handed. All participants had normal hearing and normal or corrected-to-normal vision, were of Caucasian race and had the Dutch language as their first language.

Procedures and Materials

To investigate the interrelationships between developing spelling, reading and handwriting skills the children were assessed in Grades 1, 2 and 3. The first assessment took place in February/March in Grade 1, approximately 7 months after their start in Grade 1 and 3 months after the children had started practicing graphemes with joins for cursive handwriting. They were re-assessed in February/March of Grades 2 and 3.

For handwriting, a standardized 5 minutes copying task was used which provided speed and legibility scores (Hamstra-Bletz, 1993; Hamstra-Bletz, De Bie, & Den Brinker, 1987). The copying task was given as group assignment; the results were individually evaluated by one of the authors (I.B-S). Language skills – that is, reading and spelling achievements – were pulled out of the school-based, national organized Dutch follow-up system, used by schoolteachers. The scores for reading and

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spelling from the first school assessment (January/February) were used for the current analyses. To capture motor proficiency independently from linguistic processing, an existing loop-writing task was used see: Bosga-Stork, Bosga, and Meulenbroek (2011) and Meulenbroek, Thomassen, Van Lieshout, and Swinnen (1998). The children were tested individually by the same administrator (I.B-S) in a quiet room in the school, seated on an adjustable chair, with their feet supported and in a writing position adapted to the digitizer tablet. The task took 45 minutes of time and was also administered in February/March.

The primary school's institutional review board approved the study and each year all parents of the participants gave their informed consent and all children agreed to participate. Each child received a little present after each experimental session. Experimental procedures followed the APA guidelines for the ethical treatment of human participants.

Handwriting performance

The Concise Assessment Scale for Children's Handwriting (acronym BHK) was used to assess handwriting speed and legibility (Hamstra-Bletz et al., 1987). The BHK was tested as a group assignment. Their teacher administered the test, while the children were seated at their own table in the classroom, writing with their own pen in their usual handwriting style. The test consisted of copying a standard preprinted text on a plain sheet of A4 paper during 5 minutes, or five lines if the child is a very slow writer. Handwriting legibility was evaluated by assessing 13 dysgraphia features such as for example letter size, spacing, letter distortion, acute turns, corrected letterforms. Handwriting speed was measured by counting the number of letters produced in five minutes, which can be translated into deciles scores related to the child's grade. A slow writer was defined as a child in deciles 1- 2 of their norm group (<71 letters for Grade 1; < 86 for Grade 2; < 132 for Grade 3), a typical writer as a child in deciles 3 - 8, and a fast writer as a child in deciles 9 - 10 (>98 letters for Grade 1; >141 for Grade 2; >191 for Grade 3). The interrater reliability of the BHK has been reported to vary between $r = .71$ and $r = .89$; intrarater reliability was $r = .87$ to $r = .94$ for Grade 2 and $r = .79$ to $r = .88$ for Grade 3, while the test-retest reliability was found to vary between .51-.55 (Hamstra-Bletz et al., 1987). Handwriting legibility performance was not taken into account because the BHK battery does not yield handwriting quality scores for Grade 1 and cannot therefore be used to measures change between grades 1 and 2. At the beginning of this research, the BHK was the most frequently used handwriting test for Dutch children. Although the norms are updated in the recently published shorter version, the BHK norms are still valid. For this research we will focus on differences in handwriting speed.

Language skill measures: reading and spelling

A standardized Dutch reading test (Jongen, Krom, Van Onna, & Verhelst, 2011; Visser, Van Laarhoven, & Ter Beek, 1996) for technical reading performance (AVI) was used to assess reading ability. The AVI reading score for each pupil is determined twice a year and is arrived at by asking the child to read out loud a number of age-appropriate sentences within a prescribed interval. The AVI score depends on the speed and accuracy of performance.

The standardized Dutch spelling measure assesses spelling in 25 words or sentences, varying with age. For Grade 1 the teacher dictates single words with word illustrations on the assignment page. For Grades 2 and 3 the teacher first reads a sentence out loud then a target word is dictated and written down by the children in their assignment book. From mid-Grade 2 on, multiple-choice assignments are included. The child has to find the one misspelled word in four sentences with bold target words (De Wijs, Kamphuis, Kleintjes, & Tomesen, 2010). Higher percentage reflects that the pupil learns faster, and a lower percentage reflects he/she is a slower learner in relation to the demands of the grade. We used the learning output percentage scores for the spelling and reading measures.

Loop writing performance

Loop-writing performance was evaluated using a non-linguistic loop-writing task performed with an electronic pen (Intuos3) on a digitizer (WACOM A4 Oversize tablet), which sampled the X-Y coordinates of the pen tip position at 200 Hz. The children were asked to draw loops of different height (12, 9, 6 and 3 mm, reflecting the gradual diminishing line width used in the school system) on sheets of paper with lines indicating the target heights. The task was paced by means of an acoustic signal of either 1, 2 or 3 Hz to assess the degree to which the children were able to generate requested loop amplitudes under increasing timing constraints. The pacing signal changed sinusoidal in intensity across a clearly audible range (approximately 60-70 dB; tone pitch 330 Hz). Without the influence of linguistic demands, the higher pacing frequencies challenged the children's amplitude production accuracy, which we assumed to increase the sensitivity of our assessment of the fine motor coordination required for producing handwriting. A trial consisted of six repetitions of 18 loops using the twelve amplitude-frequency combinations, which were presented at random

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leading to a total of 1296 loops per experiment in Grades 1, 2 and 3 (i.e., a maximum of 3888 loops per child). Before the experiment started, the children were allowed to practice the task a few times to get comfortable with the experimental procedure and task requirements. For this purpose, in Grade 1 each of the three frequencies was performed twice, using the 9 and 12 mm loop patterns, thus yielding 12 practice trials in Grade 1. In Grades 2 and 3 each of the three frequencies was practiced twice, using only the 9 mm loop pattern (6 practice trials).

Data analysis and statistical procedures

Preprocessing of the digitized loop writing movements involved linear interpolation of missing data points, 2nd-order, zero phase-lag Butterworth filtering with a cut-off frequency of 8 Hz and finding, by means of an automatic peak-detection algorithm, the extrema in the vertical pen-tip displacement data. The detection of extrema was visually checked, yielding a total of 1.78% trials (n=419) that were rejected. Subsequently, for each loop the differences between the instructed and performed amplitude, frequency and the standard deviation of the relative phase were calculated. For an extensive description of the analysis of the kinematic data see references Bosga-Stork et al. (2011, 2014).

Performance measures reflecting handwriting speed, reading and spelling levels and fine-motor skills were determined for each child individually. Between-subject variability within a grade was expressed in standard deviations and coefficient of variation. Between- grade performance changes were calculated by subtracting, per child, the scores obtained in Grade 1 from those measured in Grade 2 (and the scores from Grade 2 from those in Grade 3) such that for both grade differences positive scores reflected improvement in performance.

To determine the interdependencies between the investigated literacy and motor skills we choose Kendall's tau rather than Pearson or Spearman correlation coefficients, for its non-parametric properties, the absence of linear relationships between variables and the small sample under investigation (Ma, 2012). The correlations between the test scores were calculated per grade. To determine the interdependencies between the changes in the literacy and motor skills between Grades 1 and 2 and the changes of these skills between Grades 2 and 3, Kendall's tau was also determined between the difference scores between Grades 1 and 2, and the difference scores between Grades 2 and 3. To assess the developing relations between handwriting and literacy skills in slow hand writers in particular we identified in Grade 1 slow writers according to the BHK (i.e. scoring in the 1st or 2nd deciles of the norm group). Analyses were conducted in SPSS-22 with statistical significance level $\alpha = .05$.

Results

The general performance of the children for the handwriting-, language- and loop- writing performance for each grade, expressed in mean, standard deviation (SD), the coefficient of variation (CV), the minimum and maximum and confidence interval of the mean (CI), are shown in Table 1. Over the three grades the performance in handwriting increased. For reading and spelling the children increased their competence in reaching the requirements of their grades (the mean learning percentage for spelling decreased relatively in Grade 3, but still met the requirements for this grade), and the errors and the variability in coordination in the loop-writing task decreased (see Table 1).

Table 1. *Descriptive Statistics for Handwriting Speed, Language Performance (Reading and Spelling) and Loop-writing Performance (Amplitude and Frequency Errors and Variability of Coordination) differentiated for each measure for Grade 1, 2 and 3.*

					Range		**95% CI**	
Variable	Grade	Mean	SD	CV%	Min	Max	LL	UL
Handwriting								
Speed	1	57	23	41	15	100	48	65
(number of letters per 5 min)	2	125	36	29	56	203	112	138
	3	200	50	25	133	357	182	219
Language								
Reading	1	112	77	69	14	214	85	140
(learning-percentage)	2	133	67	50	29	285	109	157
	3	136	46	34	23	250	119	152
Spelling	1	95	57	60	57	243	75	116
(learning-percentage)	2	124	55	44	33	227	104	144
	3	115	36	31	27	177	102	128
Loop Writing								
Amplitude Error	1	1.52	.52	34	.67	2.64	1.33	1.71
(mm)	2	1.29	.56	44	.52	2.61	1.09	1.49
	3	1.24	.62	51	.44	3.28	1.01	1.46
Frequency Error	1	.33	.17	51	.09	.68	.27	.39
(Hz)	2	.24	.17	68	.09	.65	.18	.30
	3	.21	.13	64	.05	.53	.16	.25
Coordination								
Variability	1	67.15	5.69	8	50.46	76.14	65.10	69.21
(deg)	2	63.74	6.34	10	51.74	76.38	61.45	66.02
	3	60.74	8.08	13	46.65	73.38	57.83	63.66

The change in performance between Grades 1 and 2 and between Grades 2 and 3 for the handwriting, language and motor indices are reported separately in Table 2. For the handwriting speed and language scores a positive difference score reflects performance improvement, for the motor capacity scores the reverse is true because the measures concern error scores and coordination variability. The *p*-values of Table 2 test whether the means reported in the previous table, Table 1, are different. As displayed in Table 2, all literacy and motor scores improved significantly between Grades 1 and 2. The standardized effect size was large for handwriting speed (d = 2.23) but weaker for the other variables ($|d|$ between 0.40 and 0.69). Between Grades 2 and 3, there was a significant improvement in handwriting speed, frequency error and coordination variability, but not in reading, spelling, and amplitude error. The standardized effect size was large for handwriting speed (d = 1.92) but not for frequency error and coordination variability (d = -0.33 and -0.57, respectively).

Table 2. *Changes in performance form Grade 1 to Grade 2 and from Grade 2 to Grade 3 for handwriting speed, language measures for reading and spelling and loop-writing measures for amplitude error, frequency error and variability of coordination.*

				Range		Cohen's d			95% CI of d	
Variable	Grade	Mean	SD	Min	Max		t(31)	2-sided p	LL	UL
Handwriting										
Speed	2-1	69	31	-1.0	137	2.23	12.63	<.001**	1.54	2.78
(nr.let/5 min)	3-2	75	39	5	194	1.95	11.02	<.001**	1.33	2.46
Language										
Reading	2-1	21	51	-96	117	0.41	2.28	.030*	0.05	0.77
(learning-percentage)	3-2	3	44	-87	131	0.07	0.33	.743	-0.28	0.41
Spelling	2-1	29	57	-127	141	0.51	2.87	.007**	0.14	0.87
(learning percentage)	3-2	-9	43	-112	104	-0.21	-1.16	.257	-0.56	0.14
Loop Writing										
Amplitude	2-1	-.23	.58	-1.41	1.47	-0.40	-2.28	.030*	-0.75	-0.03
Error (mm)	3-2	-.05	.66	-1.36	1.87	-0.08	-0.46	.649	-0.42	0.27
Frequency	2-1	-.09	.14	-.33	.30	-0.64	-3.57	<.001**	-1.02	-0.26
Error (Hz)	3-2	-.04	.11	-.31	.23	-0.33	-1.87	.071*	-0.72	0.00
Coordination										
Variability (deg)	2-1	-3.42	4.98	-13.4	8.38	-0.69	-3.88	<.001**	-1.07	-0.30
	3-2	-3.00	5.23	-14.5	8.21	-0.57	-3.24	.003**	-0.94	-0.20

The rank-order correlations (Kendall's tau) between the handwriting speed production, language and loop-writing measures for each grade separately are given in Table 3.

In grades 1, 2 and 3 there were statistically significant positive correlations between the reading and spelling measures, (τ = .35, .49 and .33 for Grades 1, 2 and 3; p =. 004; .001 and .005 respectively). Reading showed a significant positive correlation with handwriting speed in Grade 1 only (τ = .37, p = .003), while spelling showed a significant positive correlation with handwriting speed in the first and second grade (τ = .36 and .39, p = .004; .001 respectively). For the motor performance domain in the loop-writing task, the error in amplitude was negatively correlated to both language measures, but only in Grade 1 (for reading τ = -.33; p = .007, for spelling τ = -.36; p =.004). Over all three grades, the frequency errors in loop-writing performance showed a significant positive correlation with the variability of coordination in this task (τ = .73, .71 and .78 for Grades 1, 2 and 3; all *p's* = .0001).

Table 3. *Summary of correlations for scores on handwriting speed, reading learning percentage, spelling learning percentage, amplitude error, frequency error and variability of coordination for Grades 1, 2 and 3 separately.*

	Language		Loopwriting		
	Reading	Spelling	Amp Error	Freq Error	Variability
Grade 1					
Handwriting Speed	.373 **	.356**	-.159	-.129	-.235*
Reading learning %		.353**	-.329**	-.175	-.185
Spelling learning %			-.355**	-.169	-.093
Amplitude Error				-.035	.000
Frequency Error					.729**
Grade 2					
Handwriting Speed	.148	.386**	-.069	.010	-.048
Reading learning %		.494**	-.070	-.050	-.115
Spelling learning %			-.008	-.194	-.258*
Amplitude Error				-.113	-.004
Frequency Error					.712**
Grade 3					
Handwriting Speed	.156	.166	.114	-.171	-.085
Reading learning %		.332**	-.035	-.180	-.189
Spelling learning %			-.204	-.241*	-.207
Amplitude Error				-.109	.020
Frequency Error					.779**

The rank-order correlations (Kendall's tau, one tailed) for the change in performance of handwriting in relation to literacy and motor skills within grade 1-2 and within grade 2-3 are given in Table 4. Within Grade 1-2 there was a weak but significant negative relationship for handwriting speed and learning percentage for reading $\tau = -.27$, $p < .018$. Within Grade 2-3 there existed a weak, but significant positive relationship between handwriting speed and amplitude errors in loop writing $\tau = .24$, $p < .027$.

Table 4. *Summary of correlations of the changes in performance of reading, spelling (literacy), amplitude errors, frequency errors and variability of coordination (loop-writing) in relation to handwriting speed measures, between Grades 1-2 and between Grades 2-3, separately.*

Measure	Handwriting Speed
Grade 2-1 difference	
Reading Learning %	-.265*
Spelling Learning %	.098
Amplitude Error	.00
Frequency Error	.047
Variability	.045
Grade 3-2 difference	
Reading Learning %	.078
Spelling Learning %	.057
Amplitude Error	.241*
Frequency Error	.159
Variability	-.051

*Kendall's Tau-b (1-tailed: *P=<0.05)*

The development of the literacy skills for children with slow handwriting speed in Grade 1 as compared to the other children is presented in Figure 1. In Grade 1 the slow writers were those children whose handwriting speed scored in the 1st and 2nd deciles of the BHK as defined in the 1987 norm group. The other children's handwriting speed ranged between the 3rd - 10th deciles on the BHK. Twenty-four children (75%, 13 girls and 11 boys) proved slow writers whereas 8 children (4 boys and 4 girls) were not. This categorization of children on the basis of handwriting speed in Grade 1 was used to track the development of literacy and motor skills of both

groups over the three years of development. Panel A (Figure 1) shows an increasing handwriting speed over the three years, whereby the slow children in Grade 1 (straight line), remained relatively slower in Grades 2 and 3. For the development of reading and spelling performance (panel B and C) the two groups started at a different level but attained equal or nearly equal performance levels in Grade 3.

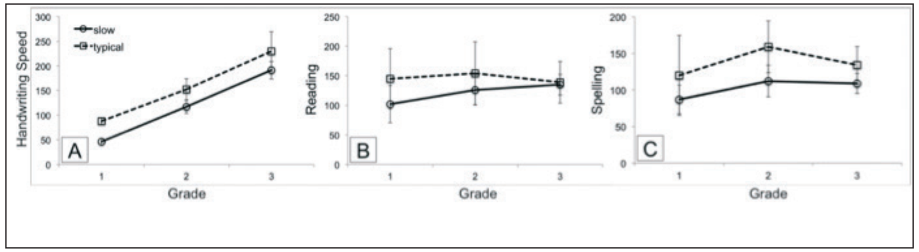

Fig. 1. *Literacy and motor development as a function of handwriting speed in the first grade. A: Handwriting speed as a function of grade for hand writers who are slow (solid line) or typical (dashed line) in Grade 1 as measured by the BHK. This handwriting-speed based split of the participants is maintained in B-C. B: reading learning percentage, C: spelling learning percentage.*

Discussion

In this exploratory longitudinal study 32 children were followed in three successive years with respect to their handwriting speed, reading, spelling, and fine motor skills (loop-writing). The group means unfolded the following pattern. From Grade 1 to Grade 3 the children showed marked progress in writing speed that was fairly consistent across individuals. The improvements in reading and spelling learning performance and loop writing were less consistent.

In Grade 1, handwriting speed had a significant positive correlation with reading, spelling, and a significant negative correlation with the coordination variability dimension of loop writing. In Grade 2, handwriting speed had a significant positive correlation with spelling but not with any of the other variables. In Grade 3, handwriting speed had no significant correlations with the other measures. These results suggest that handwriting develops into an autonomous skill that in Grade 3 becomes independent of other cognitive components. Thus, while handwriting shares cognitive resources with reading and language production skills in the first grades, it depends on its own specialized resources in the third grade. These results are in line with Berninger (2000) who formulated four functional language systems that are interconnected, but show an independent development (Berninger, Abbott, Abbott, Graham & Richards, 2002). Alternatively, these lower correlations in Grade 3 can be explained by assuming that in this grade, unlike in Grade 1 and 2, the children's spelling capacities start to match the difficulty of the transcription task. Furthermore, slow handwriting speed in Grade 1 not only persisted in Grades 2 and 3, but was also indicative of a lower spelling performance in Grades 2 and 3.

The high number of children with a slow handwriting speed development in Grade 1 was remarkable. The results and interpretations of handwriting speed measurements strongly depend on the test battery used and the moment of assessing skill performance within the school year (Hamstra-Bletz & Blöte, 1990; Graham, 1998; Mojet, 1991; Van Galen, 1991; Van Waelvelde, Hellinckx, Peersman, & Smits-Engelsman, 2012; Ziviani & Watson-Will, 1998). The fact that 75% of the children initially scored in the deciles 1-2 might be due to the timing of our assessment, which took place in February/March, whereas the norm sample of Hamstra-Bletz (1987) was tested in June. In literature the development of legibility is unambiguous, the quality of handwriting for girls is better than for boys. Differences in handwriting speed between boys and girls however, are not as clear (Berninger & Fuller, 1993; Feder & Majnemer, 2007; Graham et al., 1998; Graham, Struck, Santoro, & Berninger, 2006; Karlsdottir & Stefansson, 2002; Medwell & Wray, 2008; Vlachos & Bonoti, 2006). In our cohort there was no difference between boys and girls for the development of handwriting speed. This finding is in agreement with Feder's research (2007).

The findings in this study confirm the moderate but systematic connection that exists between reading and spelling, at least as far as they develop in the first three grades of primary school. These results are comparable to the results of the longitudinal study by Abbott et al. (2010) in which a spelling to word-reading relationship was found (Berninger, 2000; Bosman & Van Orden, 1997), although the handwriting task (PAL, Alphabet Writing) that was used in Abbott's research is not the same as the transcription task used in this study. These findings underline the necessity to look not only at the motor performance side of handwriting, but also at the development of reading as well as spelling if handwriting does not develop as expected by the teacher.

There are several limitations for this exploratory developmental study. The learning conditions were not experimentally manipulated in this study. For this reason it is not possible to draw strong conclusions about causal relations. However, if the suggested explanation of the handwriting skill becoming increasingly more automatic in Grade 3 were correct, one would predict differential effects of tasks that

introduce difficulties in reading or writing. For example, writing non-words would have a larger effect in Grade 1 than in Grade 3. Furthermore, a delay or deficiency in the development of reading or spelling might either slow down development or trigger an alternative developmental path for these skills, since reading and spelling are different in sensory input (Bosman & Van Orden, 1997, 2003). Caution is due with the interpretation of 'learning %' used for the spelling and reading task. These scores are no direct performance scores from spelling and reading tasks, but a reflection of the progress, stability or decline of these abilities over the year, compared to the learning demands of a grade for an individual child. Thus, the non-significant difference between Grades 2 and 3 for spelling in Table 2 does not mean a lack of progress in their spelling performance, but rather that their progress was average. Learning percentages are useful for individual children, since they signal fluctuation in the capacity to comply with the grades performance levels.

Further research on the individual development of children concerning the relationships between handwriting skills and language development as well as growth across the grades of reading, spelling and motor skills is warranted. Differences in individual capacities and adaptability within children belonging to one grade need to be looked into in order to make solid choices for remediation. Nowadays most handwriting research is concentrated on differences between normal and dysgraphic handwriting development and kinematic features of these differences, for example as shown by Chang & Yu (2013) and others (Khalid, Yunus, & Adnan, 2010; Kushki, Schwellnus, Ilyas, & Chau, 2011), while interactions between language and writing are covered by many authors (Afonso & Alvarez, 2011; Kandel & Perret, 2014; Pontart et al., 2013). However, studies that combine the underlying skills of handwriting development in school settings, aimed at the interactions at the level of developing skills are scarce. An exploratory study is a start to reach these goals.

Implications for primary education

For teachers and therapists, slow handwriting speed development, is often a first indication that the complex skill involving perceptual, motor and language capacities might show an unexpected delay. Children in the first years in primary school are generally not yet (fully) diagnosed for possible learning disorders. Assessment of handwriting might therefore be a good starting point for differentiating learning disorder. Since slow handwriting speed development in Grade 1 is, at least for this group and at this moment in their education a common occurrence, it presumably is not an indication of spelling or reading difficulties. In handwriting assessments the timing of assessment in first grade is essential. Depending on the school curriculum, handwriting, spelling and reading all have their different and individual developmental timespan. At the end of Grade 1, typical developing children should be able to reach acceptable handwriting speed. At the end of Grade 1 and in Grades 2 and 3, literacy skills should be taken into account when assessing an individual child's handwriting performance, since slow handwriting speed is not prevalent in these grades and handwriting speed performance in relation to spelling and reading capacities offer a wider perspective on motor performance in the context of educational goals. Assessment of handwriting development in a school setting could be further deepened by kinematic analysis of handwriting movements using dual task measurements for perception (visually and auditory) and action (by hand), as measured in the loop-writing task used in this study. Line spacing constraints are often prescribed and incorporated in the handwriting methods in the Netherlands to induce normative handwriting size. Differences in capacities to cope with speed and precision should also be taken into account when defining line spacing instructions.

The inclusion of a device for kinematic analysis of children's handwriting movements in a school setting is not unthinkable in the near future, since data analyses become more and more sophisticated and easy to achieve (Accardo et al., 2007), although interpretation of the data might need a remedial team consisting of teachers and pediatric therapists. Although legibility has not been taken into account in this study, for purposes of diagnosis and treatment it seems important to track legibility alongside speed even though legibility develops sooner than speed and both need different remedial approaches (Karlsdottir & Stefansson, 2002).

Conclusion

The interrelations between developing handwriting speed and the literacy skills reading and spelling in the first three grades of primary skills were moderate but systematic, and more important than the slowly developing fine-motor skills. Development of slower handwriting speed in Grade 1 was likely to persist in Grades 2 and 3, which was correlated with reduced capacity to comply with the learning demands for spelling. As a basis of teachers' and therapists' judgment it is advised to assess the pupil's handwriting as well as reading and motor skills, while recognizing the fact that assessment timing might define the outcomes.

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Chapter 6

Dysgraphic Handwriting Development and Inclusive Education: The Role of Interdisciplinary Counseling

CHAPTER 6

Dysgraphic Handwriting Development and Inclusive Education: The Role of Interdisciplinary Counseling

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Abstract

With 'inclusive education' in the Dutch school system in mind, a new interdisciplinary counseling was conceptualized. Failing handwriting development in Grade 1 was scrutinized to explore the possibilities of interdisciplinary counseling. The development of two children with dysgraphic handwriting was followed in Grades 1, 2 and 3, and contrasted with the general results of their classmates. Teachers, pediatric physical therapist and psychologist used a combination of handwriting, literacy and kinematic measures for assessment and interdisciplinary counseling for diagnosis and decisions on treatment for the two children with dysgraphic handwriting development. For handwriting speed and quality, standardized test scores were used, for spelling and reading, measures from the school following system were extracted. A motoric loop-writing task was used to explore non-linguistic motor development. For the two dysgraphic boys, a combination of handwriting assessment, kinematic assessment, and reading and writing capacities seems to be a sound foundation for interdisciplinary counseling. Dyslectic development proved to be easier to differentiate than visual motor learning disorders. The handwriting test we used (BHK), can distinguish dysgraphia in general by low scores on quality, whereas the handwriting speed might be informative for developmental dyslexia. Speed and spelling combinations are distinctive for developmental dyslexia, but not so for visuo-spatial learning disorders. Spatial accuracy in a non-linguistic task is also distinctive for dyslexia, especially in first and second grade, while visuo-spatial learning disorders cannot be distinguished by spatial accuracy in a non-linguistic task. Our conclusion is that, if obvious measures for remediation of dysgraphic development are insufficient, psychological assessment is imperative for defining underlying disorders. Tacit knowledge and practical experience in teachers as well as theoretical and practical knowledge of the pediatric physical therapist, together with solid diagnosis to define constraints for treatment procedures, are needed to start the process of inclusive education in elementary schools.

Introduction

Recently substantial changes were made to the Dutch educational system, with the aim to integrate children with 'special educational needs' in the existing school system. Elementary schools now have an obligation to provide educational settings for children, fitting their qualities and abilities summarized in terms of 'appropriate education' and 'duty of care'. This has resulted in an educational model that can be phrased as 'usual where possible and special when needed' and 'no child left behind', following the general international trend of integration and inclusion for children with special educational needs (Ainscow, 2005; Ainscow, Howes Farrell, & Frankham, 2003). Integration nevertheless is not an easy process. In practice, a medical dysfunction paradigm is often used for children with special needs, which presumes the validity of qualitative differences between typically and atypically developing children, but proceeds in treating the dysfunction in order to keep the children in a regular existing education program. Inclusion captures an altogether other concept, which leaves the, often unchangeable, dysfunction in place and focuses on trying to adapt the environment (Barton, 2003; Schuman, 2007; Terzi, 2005). Theoretically, inclusion is more in line with dynamic-system or ecological-psychology principles, where behavior is the result of a combination of the child's abilities, the task and the environment (Newell, 1986; Sugden & Henderson, 2007). The diversity among children is thus supported and explored in order to define alternative programs for learning.

Currently, the introduction of inclusive education in the Netherlands is still overpowered by the process of procedures and system changes and teachers are reluctant to embrace the consequences of inclusive education, but individual teachers are well aware that their experience and expertise is needed for changes on the work floor (De Boer, Pijl, & Minnaert, 2011; Pijl, 2010; Schuman, 2007). In the wake of the Dutch government policy changes, new partnerships have evolved (Thijs, Van Leeuwen, & Zandbergen, 2009). Within school settings in nine cities in the Netherlands, we have started interdisciplinary teams ('Expertise Centrum Uniek') of psychologists, pediatric speech therapists and pediatric physical- and occupational therapists, family counselors and dietitians, exchanging assessments and experience with teachers. Instead of assessing the children at different locations where several specialists assess and treat children and advising teachers, without knowledge of each others interventions, we now work close to the educational setting in order to develop a process of interdisciplinary counseling (i.e. interdisciplinary team consultations), encouraging discussions and cooperation. At the same time we aim at avoiding adverse messages for parents and teachers coming from different specialists. In this paper we report this new way of interdisciplinary counseling in view of the individual assessments and subsequent treatment decisions for two boys experiencing comparable slow and illegible handwriting development in Grade 1 but stemming from different learning disorders.

Handwriting is a complex skill that requires formal instruction in the first three years of primary school. Handwriting is more than a motor act alone, it is fundamentally a core cognitive process for the development of writing skills in general. To develop skilled handwriting, an integration of perceptuo-motor and spelling and reading capacities is necessary (Abbott, Berninger, & Fayol, 2010; Berninger, 2000; Berninger et al., 2006; Berninger, Fuller, & Whitaker, 1996; Childress, 2011; Flower & Hayes, 1981; James & Gauthier, 2006; Jones & Chirstensen, 1999; Rijlaarsdam & Van den Bergh, 2006; Van Galen, 1991). Reading, spelling and writing by hand are known to be learned in a multimodal fashion. Writing letters by hand results in better recognizing the letters while reading and also results in better spelling when compared to letter typing (Cunningham, 1990; Longcamp, Anton, Roth, & Velay, 2003; Longcamp et al., 2008). Research is clear on the fact that difficulties in spelling and handwriting affect written expression (Berninger et al., 2006; Graham & Harris, 2006). Over the years much attention is given to interventions for dysgraphic handwriting development, defining how to instruct letter and word formation (Chartrell & Vinter, 2008; Berninger et al., 1997; Graham, Weintraub, Berninger, & Schafer, 1998; Jones & Christensen, 1999). In school systems, handwriting methods have incorporated this knowledge. Nevertheless, the individual differences in talent, maturity, experience, cognition and rate of development are characteristic for children in the first three years of handwriting development. For example, research shows that the season of birth is related to achievement and diagnosis of specific learning disorders (Martin, Foels, Clanton, & Moon, 2004; Oshima & Domaleski, 2006). As regards handwriting development, some children start too young and have a short attention span, sometimes loosing grip on letterform instructions and consequently show slow progress. This can, in some cases, be a hindrance for (written) reading and spelling production (Longcamp et al., 2003, 2008). Overall, learning to write by hand is an ongoing adaptive process of tuning perceptuomotor and attention abilities to linguistic targets. Since handwriting development is primarily supported by the school system, communication between teachers and therapists is imperative (Effgen, Chiarello, & Milbourne, 2007). To enable teachers and therapists to start a process of interdisciplinary counseling for children with handwriting dysfunction, we developed an experimental assessment procedure to facilitate detection of motor problems due to failing handwriting development in the face of the complexity of literacy skills. The proper assessment of handwriting development seems in need of interdisciplinary teamwork, since about 7 - 27 % of typically developing children are reported to experience serious problems in mastering the complex skill of handwriting, while not yet being diagnosed for possible learning disorders (Feder & Majnemer, 2007; Hamstra-Bletz & Blote, 1993; Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011; Smits-Engelsman, Niemeijer, & Van Galen, 2001; Smits-Engelsman, Van Galen, & Michels, 1995).

In this study, two boys, who showed a dysgraphic handwriting development in Grade 1, were followed over three years of literacy development. The individual development of the two boys was contrasted with the general development of their schoolmates. Handwriting quality and speed measures, together with kinematic measures, were collected to define the motor capacity, while spelling and reading measures from the school following system represented literacy. After the first interdisciplinary counseling between teacher and pediatric physical therapist, a further assessment of the psychologist was proposed and added to define the constraints resulting in learning disorders. The implications for the treatment choices for the individual boys are discussed in the light of interdisciplinary considerations.

Method

Participants

In first grade, two boys (6;9 and 7;4 years of age, both right handed) in this study showed a disability to produce legible handwriting. At the end of second grade, one boy was diagnosed with dyslexia by the school educationalist, while the psychologist diagnosed the other boy with a visual-spatial learning disorder (see footnote p. 142). The boys belonged to a group of thirty-two children who attended a primary school in the center of The Netherlands, where an interdisciplinary team was based. They all were followed in 1st, 2nd and 3rd grade and participated in all sessions. The group consisted of fifteen girls and seventeen boys with a mean age of 7;1 (years; month) in Grade 1 (range 6;4 - 7;6). Four girls and two boys were left-handed. All participants had normal hearing and normal or corrected-to-normal vision, were of Caucasian race and had the Dutch language as their first language.

Procedures and Materials

To investigate the interrelationships between developing spelling, reading and handwriting skills the children were assessed in Grade 1, Grade 2 and Grade 3. The first assessment took place in March in primary grade, where printing letters just finished, they starting to learn cursive handwriting. The children were re-assessed in the same month in Grade 2, with a last assessment, also in March in Grade 3, when starting intermediate grade. For the language skills we extracted the mid-grade rating out of the school-based following system for reading and spelling. For handwriting, a copying task was used and scored with a standardized scale reflecting legibility and speed. To capture motor proficiency in the absence of linguistic processing, a loop-writing task was used (Bosga-Stork, Bosga, & Meulenbroek, 2011; Meulenbroek, Thomassen, Van Lieshout, & Swinnen, 1998). For the loop-writing spatial and temporal demands were manipulated by imposing different target amplitudes, and an acoustic pacing signal. The scores of two children identified by the standardized handwriting scale as having a dysgraphia in Grade 1, were contrasted with the group data.

The primary school's institutional review board approved the study and each year the parents of the children gave their informed consent and all children agreed to participate. Each child received a little present after the experiment. Experimental procedures followed the APA guidelines for the ethical treatment of human participants.

Language skill measure: reading and spelling

For each child in each grade, language-performance measures were extracted from the standardized child educational monitoring system (LOVS), which is used by schools to identify students with difficulties and to plan appropriate support. The test scores of the LOVS reflect the impact of the offered education at three different levels: the individual student, group results and school achievement as a total. The tests are developed by the CITO (Central Institute for Test Development), and comply with the criteria for quality of COTAN (Dutch Committee on Test and Testing). The spelling test scores from the mid-grade evaluation period were used. For the individual child the LOVS system calculates, among other measures, a 'didactical age' expressed as the sum of all educational months, with a total of 10 months for each school year, a 'didactical age' equivalent for a specific test score, expressed in educational months, and a learning output percentage (LOP) as a relative norm score. A LOP of 100% means that a pupil meets the learning demands of his/her grade, a higher percentage reflects that the pupil is a fast learner, a lower percentage reflects he/she is a slow learner. Finally the LOVS has an A to E score in relation to national scoring levels (followed by the LOP in brackets, which differs slightly for grade, adapted by the LOVS to grade and national mean): A: 25% of highest scores (LOP:>116%); B and C: 25% just above and 25% just below national level (LOP 84-116%); D: 15% below national level and E (LOP: 83-67%): 10% of lowest scores (LOP <66%).

Two language measures were included in the present study. The first, AVI, a test package for reading (Visser, Van Laarhoven, & Ter Beek, 1996) is taken individually, measuring how fast children read under speed and accuracy constraints that are appropriate for their age, the second, the Spelling Test (Cito, 2006), which gauges spelling in writing words to dictation, is taken in group session in the classroom. Both measures are expressed in terms of learning output percentage.

Handwriting product performance

The Concise Assessment Scale for Children's Handwriting (acronym: BHK) (Hamstra-Bletz, De Bie, & Den Brinker, 1987) was used to assess quality (legibility) and speed of handwriting. For Dutch children the BHK is the most frequently used test. This test is still valid in comparison to the in 2014 published shorter version, which uses only six items for screening purposes (Smits-Engelsman, Van Bommel, & Van Waelvelde, 2014; Van Waelvelde, De Mey, & Smits-Engelsman, 2008). Furthermore the handwriting speed norms are in agreement with the SOS speed norms (Hellinckx, Peersman, & Smits-Engelsman, 2012). The quality score is norm-referenced for children in Grade 2 and 3 and the scoring for speed uses norm-scores for children in Grade 1-6. The test consists of copying a standard text for 5 minutes, or five lines if the child is a very slow writer. The test was administered in a classroom setting and all children were asked by their teacher to copy a preprinted text on a plain sheet of A4 paper using their usual pencil or pen. Handwriting quality was evaluated by assessing 13 performance characteristics, i.e. (1) writing too large; (2) widening of left-hand margin; (3) bad letter or word alignment; (4) insufficient word spacing; (5) acute turns in connecting joins of the letters; (6) irregularities in joins and/or absence of joins; (7) collisions of letters; (8) inconsistent letter size; (9) incorrect relative height of the various kinds of letters; (10) letter distortion; (11) ambiguous letter forms; (12) correction of letter forms and (13) unsteady writing trace. The first two items are scored on the basis of the entire written work. Both items are measured on an ordinal scale with six categories resulting in a score form

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0 to 5. For the first item (size of writing) the actual size of the letter is measured using a transparent sheet provided by the test. This size is converted to a score from 0, which stands for appropriate for age) and 5, which is much too large for age. For item 2, the transparent sheet is used as well, measuring the slope of the left hand margin from no deviation from the straight line (0) to strong deviation from the straight line (5). For the remaining 11 items, the first five sentences are scored as to whether or not a particular feature is present in that sentence. A score of 1 is given when present, with five sentences to score, the maximum score for each feature amounts to five. The child's total score on all 13 items is categorized according to whether their handwriting is in the typical range, or 'not-dysgraphic' (a score of 0-21), ambiguous (22-28) or whether they are considered to have a handwriting difficulty referred to as 'dysgraphia' (29 or higher). The quality of the handwriting was assessed independently by two experienced pediatric physical therapists. When no agreement was reached, a third experienced pediatric physical therapist was consulted whose opinion was decisive. Since there are no norm-references for children in Grade 1, two experienced teachers were asked to apply one of the three categories, by analyzing the quality of the handwriting using their knowledge of developing handwriting. On two children there was no agreement, a third teachers' opinion was decisive. Handwriting speed was measured by counting the number of letters produced in exactly five minutes and translated in deciles scores related to the child's grade. The deciles 1 and 2 reflect a slow writer, while deciles 9 and 10 reflect a fast writer. Those in between were categorized as 'typical writers'. Interrater reliability of the BHK varied between $r = .71$ and $r = .89$; intrarater reliability was $r = .87$ to $r = .94$ for Grade 2 and $r = .79$ to $r = .88$ for Grade 3, while the test-retest reliability has been reported as .51-.55 (Hamstra-Bletz et al., 1987).

Kinematic performance

Handwriting performance was further evaluated using a non-linguistic loop-writing task performed with an electronic ink pen (Intuos3) on a digitizer (WACOM A4 Oversize tablet). Paced by means of an acoustic signal, the children were asked to draw loops of different heights (3, 6, 9 and 12 mm) and frequencies (1, 2 and 3 Hz). The pacing signals changed sinusoidal in intensity across a clearly audible range (approximately 60-70 dB; tone pitch 330 Hz). Each of 12 preprinted trial sheets consisted of six repetitions (block) of the twelve amplitude-frequency combinations and was presented at random. Amplitude-frequency combinations within the six trials of a block remained constant. Each child was asked to perform

72 trials of 18 loops each, leading to a theoretical total of 1296 loops per experiment at age 7, 8 and 9 (i.e. a maximum of 3888 loops per child). On-line recordings of X, Y and Z (axial pen force) were sampled at 200 Hz. Before the experiment started, the task was explained and the children allowed performing the task a few times to get comfortable with the experimental procedures and task requirements. For this purpose, each of the three frequencies was performed twice, using the 9 and 12 mm loop patterns, thus yielding 12 practice trials, in Grade one. In grades two and three each of the three frequencies was practiced twice, using only the 9 mm loop pattern (6 practice trials). The children were tested individually in a quiet room in the school, seated on an adjustable chair, with their feet supported and in a writing position adapted to the digitizer tablet.

Statistical Analysis

A reliability analysis was carried out for the thirteen items of the BHK, in order to be certain that the analysis of the handwriting product was sufficiently homogeneous for this specific group and could be used as reference for two children with learning disabilities. The reliability of the handwriting scale (BHK) proved sufficient. In Grade 2 Cronbach's alpha amounted to 0.70, in Grade 3 Cronbach's alpha was 0.82. Correlations between all pairs of test scores at each grade were explored to isolate interdependencies. Those literacy skills that that were significantly correlated (either positively or negatively) were further analyzed by means of linear regression analyses in which the children's individual scores were the dependent measures. To highlight the specific development of the two boys, the speed and quality measures of the handwriting task, the reading and spelling measures for the literacy and the absolute error of the amplitudes (AEAmp) of the loop-writing task were used, based on the correlations we isolated and which might fit with our experimental assessment procedure. Furthermore we included the handwriting quality measure, since handwriting quality and speed are considered to be two independent measures for handwriting proficiency. For the loop-writing task, the 18 loops of 72 trials per age were used to define the mean of the differences between the instructed and realized amplitudes and frequencies. For the exact method for analysis we refer to reference 39. The critical alpha was set at $p = 0.05$. SPSS 19 was used for the statistical analyses.

Results

General group performance

The means, standard deviations (SD) and minimum and maximum scores for the handwriting-, language- and loop-writing performance for the children in each grade are shown in Table 1. The general performance shows an increase in proficiency in handwriting speed and quality. For reading the group shows in increase of the competence in reaching the requirements of their grade, while this competence for spelling does show an increase from grade 1 to 2, but in grade 3 the competence for spelling seems to stabilize, nevertheless the groups mean is still well above the requirements for grade. For the kinematic measures, the errors in amplitude and frequency for the loop-writing task decrease.

Table 1. *Descriptive statistics for Handwriting speed and quality, Language performance (Reading and Spelling LOP) and Loop-writing performance for Amplitude (AEAmp) and Frequency (AEFreq) errors, differentiated for each measure for all children in Grade 1, 2 and 3.*

	Grade 1		Grade 2		Grade 3	
	Mean [SD]	Min - Max	Mean [SD]	Min - Max	Mean [SD]	Min - Max
Handwriting speed	57 [23]	15 - 100	125 [36]	56 - 203	200 [50]	133 - 357
Handwriting quality	-	-	18 [7]	5 - 37	15 [9]	2 - 43
Reading (LOP)	112 [77]	14 - 214	133 [67]	29 - 285	136 [46]	23 - 250
Spelling (LOP)	95 [57]	57 - 243	124 [55]	33 - 227	115 [36]	27 - 177
AEAmp (mm)	1.52 [0.52]	0.67 - 2.64	1.29 [0.56]	0.52 - 2.61	1.24 [0.62]	0.44 - 3.28
AEFreq (Hz)	0.33 [0.17]	0.09 - 0.68	0.24 [0.17]	0.09 - 0.65	0.21 [0.13]	0.05 - 0.53

Intercorrelations between all measures.

The Pearson product-moment correlations between handwriting production, language and loop-writing performance for each grade separately are given in table 2. Handwriting speed shows a significant positive correlation with reading and spelling in Grade 1 (r = .51 and .39 respectively) and Grade 3 (r = .39 and .37 respectively) but only with spelling in Grade 2 (r = .55). Reading and Spelling were statistically significant positive correlated in Grades 1, 2 and 3 (r = .40, .72 and .52 respectively). The absolute error of amplitude (AEAmp) is statistically significant negatively correlated with Reading and Spelling, but only in Grade 1 (r = -.45 and -.46 respectively). No correlations were found in the frequency domain.

Table 2. *Summary of correlations for scores on handwriting speed and quality, Reading Learning Percentage for spelling and reading and Amplitude and Frequency errors for the loop-writing for Grade 1, Grade 2 and 3 separately.*

Measure	Handwriting quality	Reading (LOP)	Spelling (LOP)	AEAmp (mm)	AEFreq (Hz)
Grade 1					
Handwriting speed	-	0.51**	0.40*	-0.30	-0.21
Handwriting quality		-	-	-	-
Reading (LOP)			0.41*	-0.45**	-0.20
Spelling (LOP)				-0.47**	-0.06
AEAmp (mm)					-0.23
Grade 2					
Handwriting speed	-0.14	0.24	0.56**	-0.08	0.01
Handwriting quality		-0.17	-0.13	0.06	-0.03
Reading (LOP)			0.72**	-0.07	-0.12
Spelling (LOP)				-0.01	-0.30
AEAmp (mm)					-0.33
Grade 3					
Handwriting speed	0.10	0.39*	0.37*	0.08	-0.28
Handwriting quality		-0.04	-0.23	0.16	-0.09
Reading (LOP)			0.52**	-0.10	-0.21
Spelling (LOP)				-0.11	-0.06
AEAmp (mm)					-0.09

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Handwriting speed and quality

Next we examined handwriting production speed as a function of the handwriting quality score (Fig. 1). In Grade 1, the general performance of children just started practicing cursive handwriting shows a wide spread for the speed and quality scores, which over the grades clusters toward the norm for age (Figs. 1A and 1B). In Grade 3, nearly all children could write sufficiently fast and neatly (Fig. 1C).

The boy diagnosed with dyslexia (square) started handwriting production in slow speed in Grade 1 (18 letter/min) and remained slow in handwriting speed over the three years of development (88 letters/min in Grade 2 and 155 letters/min in Grade 3), while handwriting quality was defined as dysgraphic (BHK = ≥ 29) in Grade 2 score 37; Grade 3 score 36. The child identified as having a visual-spatial learning disorder (circle) produced systematically dysgraphic handwriting in Grade 2 and 3 (score 29 and 57 respectively), but could speed up sufficiently: Grade 1: 47 letters/min, Grade 2: 139 letters/min and Grade 3; 256 letters/min. (Figs. 1A, B, C).

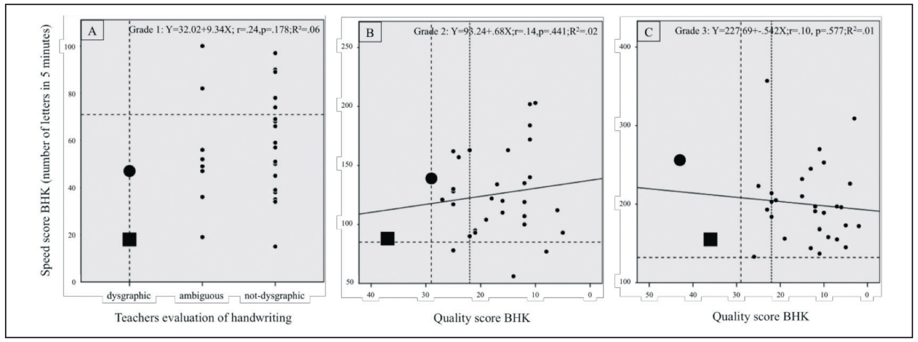

Figure 1. *Handwriting speed as a function of handwriting quality as measured by the BHK for Grade 1 (A), Grade 2 (B), and Grade 3 (C). Figure A reflects the teacher's evaluation of children who just started to practice cursive handwriting in Grade 1.*
Note: *The vertical dotted reference line in figure 1A marks the children showing dysgraphia, the horizontal dotted reference lines mark the 2nd decile for handwriting speed: BHK. The vertical dotted reference lines in 1B and 1C reflect the dysgraphic score (≥ 29, wider dots), and ambiguous score (≤ 22, small dots).*
For all figures: *Children are plotted as points around the regression lines. In all figures, the black square marks the child with dyslexia, the black circle the child with visual-spatial learning disorder.*

Handwriting speed and spelling

The interrelationship between transcription speed and spelling performance was also examined (Fig. 2). As a group the children's spelling skill developed from wide spread performance differences (Figs. 2A and 2B) to a more clustered performance around the mean (Fig. 2C), while transcription speed production increased steadily over the three years (Figs. 1A, B, C). The developmental pattern of the two children with dysgraphia in relation to speed and spelling performance was vastly different. The boy with dyslexia developed a serious spelling delay (LOP 57%, 33%, 27%, systematically in the lowest spelling category: E, meaning that he could not reach the requirements for Grade) in combination with slow writing speed (2nd deciles), which remained more or less stable over three years of development (Figs. 2A, B, C). The child with visual-spatial learning disorders showed spelling skills above the mean for age (LOP 160%, 140%, 136%, in B and A, A, category), in combination with a slow start in the development of handwriting speed production, followed by a high speed, but illegible handwriting production at age 8 and 9 (10th deciles; see Figs. 2A, B, C).

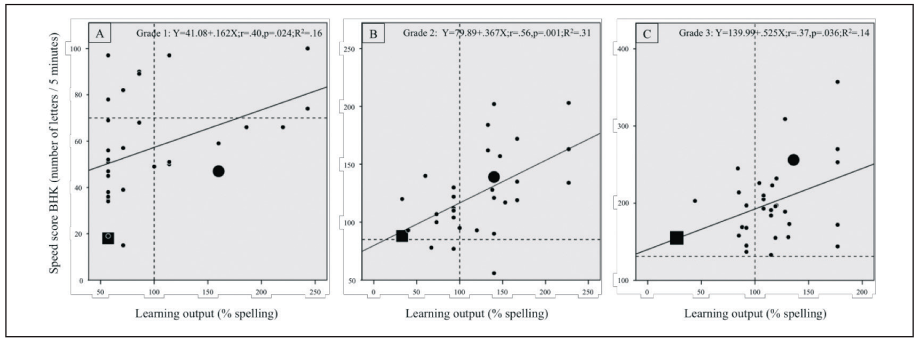

Figure 2. *Handwriting speed as a function of the learning output percentage spelling for Grade 1 (A), Grade 2 (B) and Grade 3 (C).*
Note: *The vertical dotted reference lines mark the 100% learning output for spelling. The horizontal dotted reference lines mark the 2nd decile (BHK) for handwriting speed.*

Amplitude errors and spelling

Next we looked at the absolute errors in the amplitude domain (AEamp) of the loop-writing task as a function of language spelling level (Fig. 3). At a general level a developmental trend was seen from a widely dispersed error production for children with a lower learning output for spelling towards a clustering around the mean for spelling with less amplitude errors (Figs. 3A, B and C).

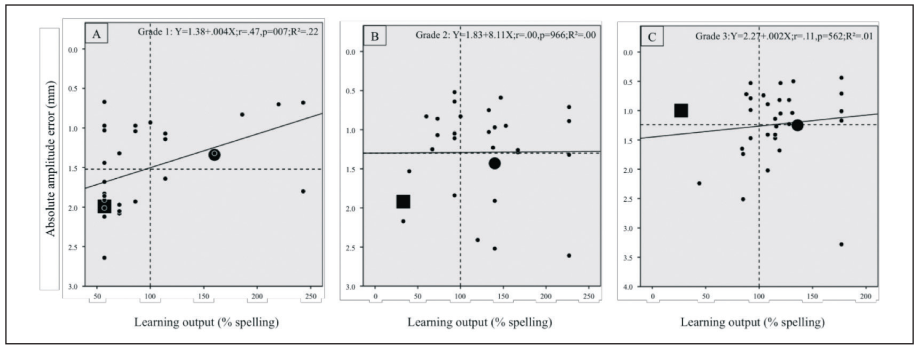

Figure 3. *Absolute Error of Amplitude (AEAmp) in mm as a function of the spelling learning output percentage for Grade 1 (A), Grade 2 (B) and Grade 3 (C).*

The children with dysgraphia were as widely apart as seen in spelling and speed combinations. In Grades 1 and 2 the boy with dyslexia showed errors of about 2 mm in the amplitude domain in combination with low levels of spelling, in Grade 3 the errors became smaller. The boy with visual-spatial learning disorder produced errors of less than 1.5 mm in combination with high levels of spelling development (see Figs. 3A and 3B), which remained around the same error level over the three years (see Figs. 3A, 3B and 3C).

Reading and spelling

Finally, the known interrelation between reading and spelling development was verified for this group (Fig. 4). At a general level a clear developmental trend was seen. While still showing diversity in performance in the different learning domains, most children showed improving learning outputs with age for reading as well as spelling (Figs. 4A, B, C).

The two children with dysgraphia performed unquestionably differently from each other. The boy with dyslexia showed a stable learning disorder with a low learning output and no progress in reading or spelling skills over the three years of development: reading LOP 14%, 54% and 23%, a performance that was systematically at the level of Grade 1, without increase in performance. The boy with visual spatial learning disorders showed a stable high learning output for reading 214%, 139% and 180%, meaning he could read well beyond his age: in Grade 1 he reached end Grade 2, in Grade 2, he reached mid Grade 3, while in Grade 3 he reached end level elementary school, thus showing no indication of developmental learning disorders in reading or spelling (see Figs. 4A, B, C).

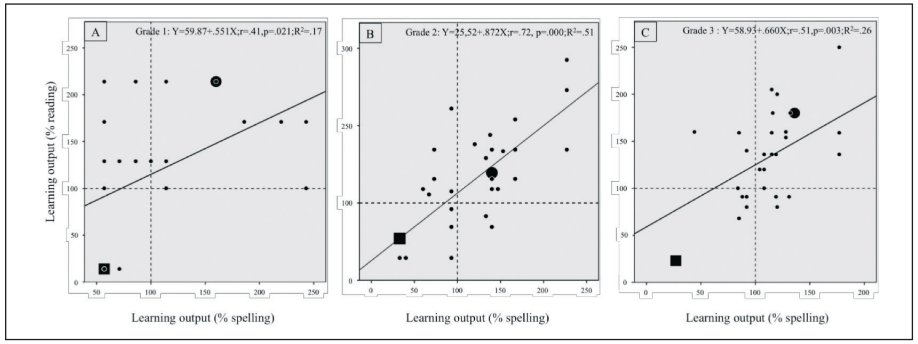

Figure 4. *Learning output percentage for reading as a function of the learning output percentage for spelling for Grade 1 (A), Grade 2 (B) and Grade 3 (C).*

Discussion

In the wake of changes in the Dutch educational system concerning children with special educational needs, a new interdisciplinary team was composed with the intention to effectuate interdisciplinary (team) counseling in school settings, respecting the diversity among children, while focusing on adapting the environment to the special needs and capacities of individual child, also known as Individualized Educational Program (IEP).

The goal of this study was to explore the practical use of a combination of performance measures of literacy and motor skills, to decide whether we would be able to isolate children with a learning disorder, expressed in dysgraphia, from their typically developing classmates, who were used as references in this study. As screening method we used a standard Dutch handwriting test for quality and speed (BHK) to define and follow handwriting development and one of the kinematic measures of loop writing (absolute error of amplitude), to define non-linguistic fine motor movements. Since reading and spelling capacities are known to relate to handwriting development, we included standardized learning-output percentages for reading and spelling, extracted from the schools' educational monitoring system. These percentages reflected whether the child was to be considered a slow, typical (normal spread around the mean) or fast learner. Finally, the psychologist set the diagnoses and defined the constraint for the specific learning disorders.

The process of interdisciplinary counseling

Step 1.

At the start of handwriting development at the age of 7, halfway through Grade 1, when just starting to write cursive, two boys in this cohort were judged to develop dysgraphic handwriting by their teachers. Following a the first assessments in march by the teacher and physical therapist, both children started an intervention using explicit instruction in motor and orthographic component using visual cues and verbal mediation (Berninger et al., 1997) aimed at legible handwriting in combination with extra tutoring in spelling and reading for the dysgraphic boy with E levels for reading and spelling. Over the first half of Grade 2, neither boy showed progress in legibility and after counseling the decision was made to initiate psychological assessment for both children.

Step 2.

The psychologist diagnosed the boy with E-levels for reading and spelling with dyslexia (DSM-5 Specific Learning Disabilities, SLD). Dyslexia is a specific disorder in reading and spelling and is treated by a specialized psychologist, the psychologist also instructs the parents and teacher. The child with dyslexia thus enrolled in the standard (Dutch) dyslexia program in combination with a yearly short-lasting handwriting training, to focus on form conservation and enough speed. Acceptance of slow handwriting is essential, since these children can write legible but are slow learners, while spelling and reading constraints affect handwriting speed (Kandel & Perret, 2015). Handwriting tasks were adapted to the constraints of dyslexia, i.e. tasks were shortened if necessary and slower handwriting speed was incorporated in the classroom assignments.

The boy with A-levels for reading and spelling could write legible directly after treatment in Grade 1, but his handwriting deteriorated over the next months and resulted in a fast production of near doodles. The consulted psychologist diagnosis was a visual-spatial learning disorder (VSLD), resembling what is sometimes called Nonverbal Learning Disability (NLD)[1]. After interdisciplinary considerations and parent and child consultation, handwriting was thought not to contribute to his learning capacities and he was taught typing in Grade 3, in combination with instructions of planning skills. At home as well as in school this boy was unable to organize his environment and needed well-defined and strict instructions and work plans (Marmarella & Cornoldi, 2005; Vidal, Meckler, & Hasbroucq, 2015).

Although both boys were dysgraphic in handwriting performance, they were treated differently, based on the different assessment outcomes for the motoric- and language capacities and different constraints arising from diagnoses.

Outcome of experimental procedure

Measure 1 (Fig. 1): Handwriting speed production in relation to quality.

Both boys showed dysgraphic handwriting over the three years, but only the boy with the dyslectic learning disorder could be singled out on speed. He remained slow in developing handwriting speed and only after three years reached an acceptable speed for his age and disorder. He remained dysgraphic on handwriting tests, although his handwriting became legible. This is in accordance with the work of Karlsdottir and Stefansson (2002), who found a weak positive but nonlinear correlation between handwriting quality and speed, describing them as approximately independent measures of handwriting proficiency. Furthermore, Peverly (2006) suggests that greater transcription speed increases automaticity of word production so that a writer's working memory can be freed up for cognitive processes, which is one of the difficulties for dyslectic children. It could be concluded that at this level of assessment, speed as well as legibility, more specifically their interrelationship, seem an essential part of diagnostic procedures when looking into dysgraphic development in the first three years of handwriting development.

Measure 2 (Fig. 2): Speed production in relation to spelling capacity

Only the boy with dyslexia could be identified as different from the group mean. For the child with VSLD, this test only tells us that spelling development is typical in the face of his peers, while handwriting speed production increases as handwriting quality declines. Here one could speculate that motor capacities might not be the core of this visual-spatial learning disorder. The differences between these boys indicate that this measure might be useful in the diagnostic process and during interdisciplinary counseling.

Measure 3 (Fig. 3): Spatial accuracy in loop writing in relation to spelling

In the domain of spatial accuracy, the boy with dyslexia showed a greater amplitude error than the child with VSLD, but his spatial accuracy increased and in Grade 3 equaled his classmates. This task is thought to express motor capacity without language interference and is a measure for the extent of motor deficiency in handwriting skill. It could be speculated that the boy with VSLD showed no primary motor output disorder, but a more cognitive processing disorder, which became apparent in the psychological assessment, were all tests concerning visual perception caused problems. The boy with dyslexia at the other hand, although afflicted with a primary language disorder was unable to develop motor efficiency (slow handwriting). The learning capacity for spelling of the boy with dyslexia remained in the lowest 25% of his grade, accuracy in motor performance developed slowly, which might indicate a language related disorder and a trainable letter formation. Here again the child with dyslexia could be singled out, which was impossible for the boy with VSLD. For this child defining the cognitive capacity through psychological assessment was essential, followed by interdisciplinary counseling to decide on learning strategies for this child.

1 *The DSM-V does not have a separate diagnosis for Nonverbal Learning Disorders, the diagnosis of NLD was given by an extern psychologist, following IQ testing (WISC) and observations.*

Measure 4 (Fig 4): Reading and spelling relations

Reading and spelling capacity for the boy with dyslexia stood out against the capacity of his classmates, while the boy with VSLD showed a capacity well within the mean of his classmates. Again for dyslexia this relation is informative, for VSLD more information is needed, especially diagnostic procedures and information on executive functions.

In conclusion, failing handwriting development in Grade 1 was used to explore the possibilities of counseling in an interdisciplinary team. In this case, a combination of handwriting assessment, kinematic assessment, and reading and writing capacities seems to be a sound foundation for interdisciplinary counseling. The handwriting test we used (BHK), can distinguish dysgraphia in general by low scores on quality, whereas the handwriting speed might be informative for developmental dyslexia. Speed and spelling combinations are distinctive for developmental dyslexia, but not so for VSLD. Spatial accuracy in a non-linguistic task is also distinctive for dyslexia, especially in first and second grade, while VSLD cannot be distinguished by spatial accuracy in a non-linguistic task.

When obvious measures for remediation of dysgraphic development prove to be insufficient, psychological assessment is imperative for defining underlying disorders. Tacit knowledge and practical experience in teachers as well as theoretical and practical knowledge of the pediatric physical therapist, together with solid diagnosis to define constraints for treatment procedures, are needed to start the process of inclusive education in elementary schools.

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6

Chapter 7

General Discussion

CHAPTER 7

General Discussion

This chapter contains a general discussion of the five studies on preparatory handwriting reported in this thesis. We also reflect on the possible implications of our research for pediatric physical and occupational therapists in following procedures of assessment for children with atypical handwriting development.

An exploration of the developing process of controlling spatio-temporal goals in a loop-writing task was the starting point of underlying longitudinal study. The main research question addressed in this thesis concerned the development of motor capacities as seen in a letter-like, language-free loop-writing task and the interactions between motoric, cognitive- and language processes in developing handwriting of primary school children. The study encompassed the period when children master the handwriting skill in Grades 1 - 3, i.e. between 6 and 9 years of age. The thesis can be divided in two parts, starting at a fundamental, experimental level, ending at an ecological level, in the reality of daily educational practice.

In the first part three experimental studies are presented, exploring the decrease as well as the increase of movement variability over time, in a letter-like loop-writing task. At the one hand we looked at the development of decreasing end-point movement variability within the context of the physical degrees of freedom, reporting two studies in which we demonstrated how complex the growing relationships are between controlling movement amplitudes and frequencies of the loop writing task, monitoring one's own cyclical movements, and correcting errors while maintaining movement production at a prescribed pace. At the other hand we explored the development of increasing movement variability within the context of the dynamical degrees of freedom (Mitra, Amazeen, & Turvey, 1998), or behavioral flexibility, by using short-and long-term autocorrelations, reflecting time-dependent self-similarity in movement patterns. These findings shed light on the way children adapt to task requirements at different time scales.

In the second part of the thesis, the relationship between the cognitive (handwriting product), motoric (kinematic measures), and language performances (reading and spelling capacities) were explored and then used for an explorative, hypothesis-forming, descriptive case study, where the inter-individual variability of these interactions clearly showed up in our longitudinal study. The co-existence of strong general relationships and clear individual developmental routes are important empirical findings strengthening the body of knowledge used by physical therapists, teachers, and educationalists to construct teaching environments and make decisions regarding training and remediation for individual children who show signs of lagging behind in acquiring critical skills. Indeed, one of the practical aims of the research reported in the present thesis was to expand the physical therapist's body of knowledge so that he or she can make informed decisions in clinical reasoning concerning the remediation of atypical handwriting development of an individual child.

FIRST PART: Development, Learning and Variability in Loopwriting

Initial learning stage

Development and maturation

Chapter 2 describes the behavior of children in the initial learning stage of handwriting in Grade 1. In March, just starting to join letters, the children are able to adjust the amplitude and frequency demands of a loop-writing task at lower speed (1 Hz), but their capacity to satisfy multiple movement goals is reduced for the higher speed (3Hz). They show larger errors in the amplitude dimension than in frequency dimension and undershoot 71% of the instructed amplitude when under time pressure.

Bernstein's view that adaptive motor behavior entails exploiting the biophysics of the movement system (for an overview see: Latash, 1998) is reflected by the fact that more than half of the adjustments of amplitude and frequency in the loop-writing task were the result of exploiting natural biomechanical tendencies. A cognitive learning phase as proposed by Fitts and Posner (Beek, 2013; Magill, 2011; Schmidt & Wrisberg, 2008), is not consistent with these results, since only 32% of the parameter changes resulted from deliberate control principles.

Younger and older first graders, differing in maturity based on birth date (Martin, Foels, Clanton, & Moon, 2004), execute loop writing quite differently; although all children lagged behind to the acoustic signal with their pen movement, younger first graders produced larger frequency errors, especially in "fast and small combinations" whilst the coordination variability between pen movement and acoustic signal was relatively lower for older first graders.

In conclusion, a language free loop-writing task resembling the letter '*e*', can be used to focus on perceptual, perceptual-motor and motor performance in preparatory writers. Loop writing performance gives a remarkably broad insight in processes underlying the static handwriting product. We found that children, when first starting their handwriting training, are able to satisfy combined spatial and accuracy goals only at lower speeds, while they were less able to deliberately dissociate different movement goals. In the temporal domain the younger children produced larger frequency error that the older. The influence of maturation should therefore not be underestimated, even within a single grade. Spatial and temporal parameters such as amplitude and frequency are helpful in capturing the control strategies of first graders.

From preparatory to experienced handwriting: the longitudinal design

Development of decrease in variability and adaptation to task demands

In Chapter 3, two time-scales were used to describe developing movement efficiency in a letter-like loop writing task in children between 7 to 9 years old, residing in Grades 1, 2 and 3, the timespan in which the development from preparatory to experienced handwriting unfolds. A time scale of three years was used to focus on the development of the capacity of children to exploit the inverse relationship between movement amplitude and frequency (Fitts' Law: Fitts, 1954; Smits-Engelsman, Sugden, & Duysens, 2006). The children were able to adjust to amplitude and frequency demands, but while their responses to amplitude demands show a clear developmental change, this is less pronounced for frequency demands. Furthermore, general task performance indicated that, at these ages, small amplitudes still require too much precision and the tendencies to undershoot spatial targets as were seen at age 7 still exist, especially for the 12 mm targets. Lineation of 6 mm and 2 Hz frequencies are performed most accurately and can be seen as constraints that children accommodate to best, while 3 mm targets tend to be overshot.

A more local aspect of learning was reflected by the adaptation to task requirements at the 'settling in' time scale, were the children were able to settle quickly, that is within 2 cycles, into the loop-writing task. In general, the errors diminished between the 2nd and 3rd loop and only for the amplitude error the 2nd loop showed a developmental trait between Grades 1 and 3, while the 3rd and 4th loop remained stable over the three years of development. For the errors in frequency no differences between the ages were seen for the 2nd loop, while a slight developmental trait showed for the 3rd and 4th loop. At the level of task adaptation, the inverse relationship between amplitude and frequency was exploited and also decreased between the 2nd and 3rd cycle, showing a stable development from second grade (8 years) on. Immediate adaptation to task requirements did not show diminishing of cognitive control over the three years of development. Here task adaptation is clearly not affected by changes in learning through experience and training, as known form the learning theory by Fitts and Posner and Gentile (Magill, 2011). The imposed task constraints (metronome and prescribed linings) probably enforced planning and cognitive control on the timing of movements.

From this developmental study we learn that children at the ages of 7-9 years are not yet able to efficiently integrate auditory, visual and motor information. Learning over the years differs from learning adaptation to task requirements: while the inverse relationship between amplitude and frequency develops over the three years and show a decrease in variability, adaptation to task demands are in place from early on in development and remain fairly consistent.

From preparatory to experienced handwriting: the longitudinal design

Development of variability: increased behavioral flexibility

In Chapter 4 we adopted the view that movement variability within the context of dynamical degrees of freedom i.e. structural variability (behavioral flexibility) and self-organization are an intrinsic property of development that offers the possibility to explore the many solutions for a movement task. Here time-series analyses are used to capture time-dependent self-similarity in movement patterns that provides us with an opportunity to determine the influence of past behavior on current and future behavior. Stronger autocorrelations reflect greater time-dependent self-similarity at the level of structural variability and is interpreted to reflect more rigid behavior, while weaker autocorrelations reflect less rigid behavior i.e. more flexible behavior. Time series provide us with information at different time-scales, mirroring long-term and short-term influences on movement behavior. A relative increase in the bandwidth of coordination variability between stimulus and response may, albeit within a certain range, also indicate behavioral flexibility.

The results in this study display relative high values for short-term self-similarity, indicating that movements in the present and near future are highly influenced by information in the near past. In contrast, the values for the long-term autocorrelation functions were moderate with slightly higher autocorrelation values in Grade 1 than in Grades 2 and 3. In this study the moderate self-similarity over longer periods of time reflects the influence of information during movement preparation on the performances of the remaining part of the trial. This means that movement production is more influenced by movement preparation in first graders than in the following two years indicating higher behavioral flexibility in later years.

Rosenblum and Roman (2009) used comparable time-series analysis (fluctuation analysis) in their study on children, using a (Hebrew) handwriting task. For proficient hand writers, they found strong short-term autocorrelations (within a single letter) and more uncorrelated long-term correlations (over sentences). Children with dysgraphic handwriting differed from proficient handwriting in persistence of correlations on a longer time scale. The comparability between the above-mentioned results and our results (see Chapter 4) point out that behavioral flexibility, captured by time series fluctuation analysis, is an overarching principal in motor control of handwriting that is not burdened by language capacities.

In sum, the three studies of part one of this thesis provide us with insights regarding the differences between end-point variability and structural variability. Although end-point accuracy increases over the subsequent Grades (Chapter 2 and 3), the structure of the variability, as reflected by (non)linear time-series analysis, changes markedly over the years and is informative for the degree of adaptive capacity of the neuromotor system (Chapter 4) . Here we showed that the adaptive capabilities of children, as a measure of behavioral flexibility, increases in a non-linear fashion over time (Adolph, Joh, Franchak, Ishak, & Gill, 2009). We presume that maturation enables optimal behavioral flexibility to adjust to the amplitude and frequency demands of the loop-writing task that accounts for superior efficient task performance.

Handwriting *product measures* define atypical handwriting development (see KNGF Evidence Statement, 2009, pp 38-39) but these measures are not sufficient to specify the underlying neuro-motor processes. A combination of kinematic measures at different time scales helps to define more precisely the underlying motoric handwriting *processes* in children. Loop writing is not burdened with language-related processes and therefore might be an excellent task to differentiate between more cognitive and more motor processes that influence motor performance.

SECOND PART: Relations between Handwriting and Literacy

From preparatory to experioenced handwriting: the longitudinal design

Handwriting development in relation to reading and spelling capacities

In Chapter 5 we investigated intercorrelations for handwriting speed, kinematic measures, and reading and spelling development over the first three grades of elementary school, using an exploratory longitudinal design. For spelling and reading capacity measures we extracted the "learning percentage" from the school following system. This measure reflects the capacity of children to reach the expected level for grade. In general, over the three grades the group means showed marked progress in handwriting speed, which was consistent across individual children. Although all children received the same schooling and were focused on a predefined educational aim, their school performances for reading and spelling and the loop writing performances showed a less consistent pattern, with a striking between-subject variability in performance outcomes.

The capacity of children for keeping up with their group proved to be positively related for reading and spelling in all three grades. Furthermore, for Grade 1, handwriting speed was positively related to reading and spelling capacity as well as to the amplitude error and coordination measures of loop writing. For Grade 2, handwriting speed had a positive correlation with the spelling measure only. Looking into the changes between Grade 1-2 and Grade 2-3, slower development of handwriting speed was related to a higher learning percentage for reading and a faster development of handwriting speed was related to more amplitude errors in loop-writing performance. All relationships proved to be moderate in strength.

Surprisingly, 75% of the children of this group were defined as slow writers in Grade 1 (1st and 2nd decile, BHK), which probably is indicative for the timing of assessments (March), since handwriting speed norms for the BHK were tested in June. Apparently, a mere 3 months can make a difference but, at the same time, when split in two groups using slow handwriting speed development in Grade 1, our group still showed relatively slower speed development in Grades 2 and 3, although within the norms for typical handwriting speed for Grade. Using the same split groups, the spelling learning percentage showed the same developmental line.

As a result of this study we gained insight in the possible relations between educational, handwriting and fine-motor outcome measures. At the end of Grade 1, children should have an acceptable handwriting speed. Slow handwriting speed might be informative for reading (Grade 1) and spelling (Grades 1 and 2) disorders and vice versa. Amplitude errors, often related to line width, might hamper speed production in handwriting development.

What remains unclear is in what way intercorrelations between reading, spelling and motor measures define the end product. The performances of child should therefore be considered individually, taking into consideration that slow or abberant development of a skill might either suppress/enslave or stimulates other skills (Latash, Scholz, Schoner, 2002).

Active consultations between teacher and therapist, giving attention to reading and spelling development seems a prerequisite to arrive at calculative choices in assessment and treatment procedures. The study gives further foundation to underline the importance and promote teamwork between pediatric therapists and teachers.

Individual dysgraphic handwriting development contrasted to group performances

In Chapter 6 we turned to individual handwriting development in the context of a specific school setting. For this explorative and hypothesis forming double-case study in an ecological setting we used handwriting quality and speed measures, the kinematic measures, and spelling and reading measures from the educational following system of this specific school. We focused on two boys out of the cohort, who showed dysgraphic handwriting development at the end of Grade 1 and were followed over three years of literacy development. The individual performances were contrasted with the performances of their schoolmates. The diagnoses from the psychologist were used to define the constraints of de existing learning disorders.

This study aimed at exploring the process of interdisciplinary assessment and counseling for children with dysgraphic handwriting development. Here we described, step by step, the role of the teacher, pediatric therapist, and psychologist. Furthermore the differences between the individual children were visualized by the relationships between the different outcome-measures in relation to their schoolmates. For all children and all measures, the inter-individual differences were striking, but the large inter-individual differences seen at the start of their handwriting schooling developed into a more clustered performance around the mean, as seen in Grade 3. The changing performances of the two children with dysgraphic handwriting development contrasted sharply with the changes within the group and can be used as directives for choices in their remediation. The fact that general performance measures of a group (were the use of central tendency measures tend to 'smooth out' the results) are less informative than the actual performances of the individual children shows up strongly in this study (Grice, 2015). These findings have implications for handwriting assessments in general. The product measures we often use in handwriting assessment are not sufficient in decision-making, especially to specify more motoric defined processes. A combination of motor, cognitive and language measures help to define motoric handwriting processes in children more precisely.

General Conclusions

To decide whether or not to offer an individual child remediating help presupposes that one has a clear answer to the question which course of action in assessment, diagnosis and treatment of handwriting difficulties have already found empirical support. Empirical studies covering the effectiveness of handwriting interventions are clear on the fact that regardless of choices of treatment or duration, targeted interventions result in significant gains for most children, as long as a handwriting component is incorporated (Hoy, Egan, & Feder, 2011; for an overview see: KNGF Evidence Statement 'Motorische schrijfproblemen bij kinderen', Overvelde et al., 2011). Following these reports, comparing methods of intervention seems less informative if it is not clear which processes are scrutinized and which goal is targeted. A more meaningful way to justify choices in assessments and interventions might be to ground these choices in theoretical arguments and empirical evidence.

In the introduction we gave an overview of four different types of research (educational surveys, developmental research, cognitive analyses and motoric studies) that helps us to understand deterministic processes. Although much information can be derived from these sources, knowledge of the scope of different research lines that underlie general principles of development and learning is valuable for assessment purposes and decision-making. Treatment decisions need to be based on theoretical groundings, but the capacity of therapists and teachers to make those decisions, rests on the extent of their body of knowledge and skills.

Theoretical foundations

In the Netherlands observing the handwriting product and using the 'Procesmodel of Van Galen and Smits-Engelsman' for analyzing handwriting problems, is promoted to be used (KNGF Evidence Statement, 'Motorische schrijfproblemen bij kinderen', 2011, 5.1 p. 34). Furthermore, it is stated that the observed movements and handwriting products are the result of dynamic interactions between the individual, the task and the context and that this concept a leading principle is for analyzing handwriting problems (KNGF Evidence Statement, 'Motorische schrijfproblemen bij kinderen', 2011, 5.1 p.31). In order to broaden the perspective on theories in the field of cognitive science for handwriting assessment purposes, some theoretical frameworks are explained more elaborately below.

In the field of cognitive science several approaches to the coupling of perception, cognition and action have been formulated over the time-span of the last few decades. In the classical view perception and action are situated at different ends of the spectrum as separate components with cognition positioned as an intermediating component. In modern views, cognition is integrated in the direct perception-action link.

Information Theory Approach

The earliest model of handwriting movements (Van Galen, 1991) was based on the assumption that handwriting (as an act of communicating by putting thoughts on paper) consisted of several modules, reflected by reaction-time differences as a result of task-demand variations that were organized in a linear top-down fashion. This reductionist approach assumes that the brain is organized in relatively independent modules with dedicated functions. Motor processing was emphasized in the original model. Later, the model developed from a linear into a mixed linear-parallel model (Van Galen, 2006; Van Galen, Meulenbroek, & Hylkema, 1986). Recently, the interactions between central and peripheral processes were further explained by using a cascade model (Roux, McKeeff, Grosjacques, Alfonso, & Kandel, 2013; Kandel & Perret, 2015; Olive, 2014).

As research progressed, interactions between different levels of the neuromotor system was unraveled. Spatial accuracy in movements and neuromotor noise, i.e. noise in the neuromuscular system, were considered key factors affecting end-point variability (Smits-Engelsman & Van Galen, 1997). Based on the neuromotor noise theory, cursive handwriting tasks were used in studies of task-load effects on co-contractions and movement-time prolongations in fine motor tasks (Meulenbroek, Van Galen, Hulstijn, Hulstijn, & Bloemsaat, 2005).

Van Galen's information processing model (1991, 2006) - and its extensions by Smits- Engelsman and Nijhuis-van der Sanden (KNGF Evidence Statement, 2009; Overvelde, Smits- Engelsman, & Nijhuis-van der Sanden, 2013) - has facilitated the diagnosis of handwriting problems in terms of defining either cognitive or motoric difficulties, but falls short on identifying problems within processes underlying handwriting performance. In the case of handwriting deficits, we must take caution not to single out processes that are presumed to account for the observed deficit. If dynamic interactions between the individual, the task and the context (Newell, 1986) is to be a leading principle for analyzing handwriting problems, the information processing model, should be enlarged towards a complex system approach.

Complex System Approach

A more recent theoretical approach is the dynamical system theory that proposes behavior to *emerge* from the interplay between environmental, biomechanical and morphological constraints (Thelen & Smith, 1994) or following Newell's model, that represents the action system in which coordination dynamics emerge as a result of constraints that arise from the interaction between the individual's capacities, the task- and environmental factors (Newell, 1986). Here, behavior is presumed to emerge from a non-linear, self-organizing system (Harbourne & Stergiou, 2009; Van Orden, Holden, & Turvey, 2003, 2005; Adolph, Cole, & Vereijken, 2015). Different structures and patterns can arise from many individual parts and therefore "*it is not so much how the whole can be understood as a function of the pieces, but how the pieces can come together to produce the whole*" (Thelen & Smith, 1994, p. xix, introduction). Spontaneous changes in behavior emerge following interactions of dynamic processes occurring at any (or all) level(s) of the system. Handwriting research cannot only focus on studying the different underlying subskills *separately*, but also needs to answer the question how different sub skills are condensed to a product of skilled handwriting.

In their phenomenal book "A Dynamic System Approach to the Development of Cognition and Action", Thelen and Smith (1994) proposed two levels of observation of development, the *view from above* and the *view from below*.

The *view from above* explains the global organization across longer time spans, representing development over time. For example, fine motor skills, such as manipulative skills, follow their own developmental path. The manner in which children hold their pen shows generally known behavior. In the same way, adequately developed sound, and letter recognition skills facilitate the understanding of spelling rules that are crucial for proper handwriting development. Both develop along an individually and in time variable path and their combined performance is needed to learn the (new) skill of handwriting. What we see "from above" is mostly captured by product performance assessments.

The *view from below* describes the changes that occur on a short time-span, from moment to moment (Van Dijk & Van Geert, 2015). System intrinsic variability is assumed to be a characteristic of all behavior and a prerequisite for self-organization. For example, in our study a decrease in structural variability in loop- and handwriting behavior, as reported in Chapter 4, indicates an growing organizational interaction between sub-skills, while increasing variability is a signal of a higher degree of context dependency and is an indication of more flexibility in behavior (Thelen & Smith, 1994). For practical purposes, the 'view from below' is in need of a different class of assessment instruments. Kinematic measures and time-series analyses should find their way into the (pediatric) physical therapy practice in order to give an opportunity to therapists to go back to their roots, which is fundamentally understanding motor behavior.

The theory of direct perception-action coupling suggests that invariant features of the environment may serve as affordance for motor behavior, with behavior being directly linked to perceptual properties (Gibson, 1979; Noë & Thompson, 2002). In a similar vein, the theory of ideomotor action assumes that movements are coded as sensory consequences of an action (Girardi, Lindemann, & Bekkering, 2010). The theory of event coding (TEC) formulated by Hommel, Müsseler, Aschersleben, & Prinz (2001), suggests that perception, cognition and action planning are not isolated processes. Perception of the task goals and the relating action planning are both represented in what are called 'event codes'. Action follows as a result of the perceptual consequents of an event. Perception and action are thus viewed as a mutually overlapping process.

A further expansion in this field is the theory of embodied cognition. This theory assumes that cognition is rooted in a person's physical make-up and its interactions with the world (Wilson, 2002). Following this theory, sensorimotor areas in the brain are not only involved with action and perception, but also with word meaning, underlining that environment and action are part of the cognitive system. Word meaning can influence action execution in the same way as numbers and words such as small and large are mutually involved with action execution (Girardi et al., 2010; Van Dam, Rueschemeyer, Lindemann, & Bekkering, 2010).

These theories underline the close relationships between perception and action and underpin the dynamics of the coordination variability between external acoustic pacing and loop-writing movements that we have reported in Chapter 2 and 4.

Conclusion

In this thesis developing performance measures of handwriting quality and speed and kinematic measures of the underlying processes were combined with educational measures of reading and spelling, covering the first three years of handwriting education. The developing motor performance in handwriting was analyzed by using an acoustically paced and amplitude constrained, language-free loop writing task, which is informative for development of capacities on different levels: task performance, error correction abilities to stay within a prescribed writing area, strategy choices, maturation and learning and variability.

It is well known that teachers are quite able to recognize dysfunctional handwriting, but they lack knowledge and tools to assess the complex cognitive processes underlying motor performance (Smits-Engelsman, 1995). If teachers detect handwriting delays, the first step they need to take is to consider the educational measures of reading and spelling, since these literacy skills are informative for development of handwriting and may reflect delays in development of language skills in general. Remedial teachers and speech therapists are able to advise on such language development. Pediatric therapists are more equipped to assess motor skills. In their turn, pediatric therapists should be alert on interference of linguistic skills when assessing handwriting.

In handwriting assessment, a single performance measure for handwriting (such as the copying tast of the BHK and SOS) is informative to underscore a handwriting deficiency in school children (often already noted by a teacher); experience is needed for interpretations and task manipulation can be used to determine remaining capacities (Hullegie, Bosga, Roelofsen, Van Cingel, & Meulenbroek, 2013). However, (non)linear time series analyses are indispensible to provide insight into the underlying neuromotor processes that determine handwriting performance and are a promising new approach to handwriting research.

The dynamics of developing handwriting described in chapter 4 are in sharp contrast with the static conventions that are often adopted in clinical settings in which one is interested in capturing a child´s handwriting achievement. In such settings the traditional approach to measuring handwriting performance is focused on the quality of the static product in terms of form constancy, legibility and speed production in handwriting tasks. Thus performance with minimal end-point variability within certain time limits is considered to reflect skilled performance (Feder & Majnemer, 2003; Hamstra-Bletz, de Bie, & den Brinker, 1987; Rosenblum, Weiss, & Parush 2006; Smits-Engelsman, Bommel-Rutgers, & Van Waelvelde, 2014). Yet, the achievements of a child in handwriting tasks also depend on the interactions between the child´s developmental progress as regards the control over his or her limb dynamics and cognitive skills together with the constraints of the task at hand.

In the Netherlands, carefully defined deficiencies in handwriting development that are attributed to motoric processes and not to language- or cognitive processes are a prerequisite for starting remedial treatments by pediatric physical therapists (Overvelde et al., 2011). If handwriting products are the result of dynamic interactions between the individual, the task and the context this starting point might need some revisions. Since a dynamical system perspective indicates that for handwriting performance, language and motor aspects of the task are an emergent property resulting from the interaction between individual constraints, a more hypothetical approach towards atypical handwriting development might be preferable. The sharp demarcation between motor and language aspects for handwriting assessment might need some rethinking. Nevertheless, fine-tuned assessments of children's motor capacities are important for the pediatric physical therapist. Self- similarity as defined by long-en short term autocorrelations give a broader view on the underlying motor capacity of a child and are informative on the flexibility underlying handwriting performance. Theoretical considerations based on underlying motor processes would therefore be informative in assessments of handwriting.

The crucial question concerning the appraisal of interindividual differences and relatedly personalized educational settings, might become clearer using literacy measurements as well as more dynamic performance parameters, expressing flexibility in task performance. A simple loop-writing task is informative, but as long as technical constraints are still in place in daily practice, it seems important to consider the dynamics of age, motor experience, and task characteristics in different contexts (eg. copying-tasks, dictation, writing and exercise books) before deciding on learning strategies (Chang & Yu, 2013; Pollock et al, 2009; Thelen, 2005).

Answering the question *why* children show atypical handwriting is indeed not such a simple matter because the developing interactions of perceptuomotor and language capacities in individual children shape the emerging handwriting behavior. Of course, handwriting can be reduced to a separate skill that needs to be learned as well as practiced. As Morasso (1986) stated: '*handwriting involves a motor translation of a symbolism with a special trajectory formation*'. However, it is clear that motor skills embody an essential ingredient for handwriting, but that knowledge of the alphabetical system is also quite indispensable. In our view, motor-, cognitive-, developmental-, as well as educational research *and* underlying theories collectively are a necessary foundation for sound handwriting assessment as they not only allow the therapist to analyze the building blocks of handwriting development, but also take into account a growing body of evidence that supports the inseparable linkage between those building blocks (Thelen & Smith, 1994; Adolph, Cole, & Vereijken, 2015).

Even though many scientists adhere to a reductionist approach of the coupling of perception, cognition and action, we acknowledge that progress can be made by recognizing that the information-processing approach and the complex systems approaches (such as dynamical systems theory and ecological psychology) are in fact complementary approaches (see also Kelso, Dumas, & Tognoli, 2013). If the information processing approach ('proces model': Overvelde, Smits-Engelsman & Nijhuis-van der Sande, 2013) is used for clinical assessment in combination with process-loading tasks to assess handwriting deficiency, as proposed by Smits-Engelsman (1995) and molded in the McMaster Handwriting Assessment Protocol by Pollock et al. (2009), both language and motor-performance related neurocognitive processes can be taken into account when formulating intervention plans. In order to come to grips with the variability in handwriting development, a future perspective would be to incorporate kinematic measures in assessments procedures, in order to understand the underlying coordination dynamics. Last but not least, interdisciplinary counseling procedures should be developed if more than one discipline is involved in decision-making and treatment procedures.

Limitations and Future Research

Limitations

The selection of the two schools out of a total number of six schools that serve a greater area around a small town in the middle of the Netherlands (12.000, of which 2500 are children ranging from 5-19 years, CBS: central bureau of statistics) was a convenience choice resulting from practical considerations. The two schools merged under a single administration at the end of the study. Although a longitudinal study covers development over several years, the (relatively) small number of children (n = 34, 32), in a specific context of one Dutch elementary school warrants caution as regards data interpretation.

The specific performance changes observed in two children within this cohort, viz. those showing a similar dysgraphic handwriting development, but resulting from

different learning disorders, was highlighted in an N=2 design in an explorative, hypothesis developing study on interdisciplinary counseling in elementary school. For generalization of these findings, either more N=1 studies or studies targeting the contrasts between dyslexia and visuo-spatial learning disorders with appropriate numbers of participants are needed.

The Learning Output Percentage (LOP or in Dutch 'Leerrendement') needs special attention. The LOP is a *relative* norm score out of the educational monitoring system (LOVS) in schools. An LOP of 100% means that a child meets the learning demands of the grade, a higher percentage indicates a fast learner, a lower percentage a slower learner. The LOP is mirrored by an A-E score: A: 25% of highest scores (LOP: > 116%); B and C: 25% just above and 25% just below national level (LOP 84% - 116%); D: 15% below national level and E (LOP: 83% - 67%): 10% of lowest scores (LOP < 66%). This measure is highly relevant while following a child over the years and indicative for stability, increase or decline of the learning capacity. We choose for this measure following complications of test interpretations in daily practice. The reading and spelling tests themselves are compound measures. The AVI reading scores for example are divided in a practice and command level ('training en beheersingsniveau') per level, while half way the study both schools and at different moments, switched over to the newly advised AVI system. Furthermore, the spelling test probes different skills in each year. For the pediatric therapist the learning output percentage is indicative for the capacities of a child. This measure is less suitable for group differences and should be carefully interpreted, specifically when the developing interactions between language and motor skills in study 4 are concerned.

Future Research

Detecting children at risk, assessing a broad range of spelling, reading and handwriting skills and evaluating children's response to practice and treatment, all require reliable and solid assessment techniques. Apart from the available educational and behavioral tests, further research into new behavioral measures is indispensable. The potential of regularity statistics to capture the variability of repetitive movements is most promising (see e.g. Deffeyes, Harbourne, Kyvelidou, Stuberg, & Stergiou, 2007; Harbourne & Stergiou, 2009; Harbourne, Willet, Kyvelidou, Deffeyes, & Stergiou, 2010).

For handwriting assessment the size and structure of movement variability are both informative measures. The use of x-y tablets in clinical practice is not widely accepted, which is understandable, since the expertise to work with the recording system and knowledge to fathom the implications of the analysis is often lacking. Tools like x-y tablets and accelerometers are, however, fairly easy to manage for both therapists and children and accelerometers are small enough to use for handwriting and fine motor-task assessments. The same performance task as in the BHK, SOS and Movement Assessment Battery for Children might be used to access different measurements in the line of nonlinear analyses procedures, which widens the scope for interpretation of motor processes and goes along with theoretical view on the interrelation of perception, cognition and action. Without instruments for kinematic analysis, pediatric physical therapists depend on theoretical insights, product-performance measures, experience, and common sense. Future research will hopefully further improve pediatric physical therapy along the lines suggested in the present thesis.

Finally, the growing interest in personalized treatment and the changing insights in special educational needs are indicative for an introduction of interdisciplinary counseling, which would be greatly served by a multitude of N=1 designs.

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Summary

Samenvatting

Dankwoord

Curriculum Vitae

Summary

The present thesis reports longitudinal studies on preparatory handwriting movements, covering the period in which a group of 32 primary school children master the handwriting skill. In the first part of the thesis we describe, in three empirical studies the developing efficiency in motor control. These studies (chapters 2, 3 and 4) are based on the analysis of digitized (x-y tablet) preparatory handwriting movements obtained in a loop-writing task, resembling the graphic production of sequences of the letter *e*. In the second part of the thesis we explore the development of the relationships between characteristics of pupils' handwriting products (BHK transcription task), the kinematic measures of their motoric performance (loop-writing) and their reading and spelling performance (extracted from the school follow-up system), all collected as behavioural indices of the children's language performance skills (chapter 5). Finally, we used the measurements of the relationships among these indices for a double case study, describing two children with dysgraphic handwriting performance that were treated differently, based on the different assessment outcomes for the motoric- and language capacities and different constraints arising from their diagnoses. The variability of language-skill development at an individual level was compared to the mean of development of their age group and described from an interdisciplinary perspective (chapter 6).

For our empirical studies on developing efficiency in motor control, we used a repetitive loop-writing task to probe the motoric and cognitive development at a kinematic level. Loop writing is a non-linguistic, letter-like handwriting task, resembling connecting a sequence of the letter *e* over an extended period of time. In essence, the task can be modeled as the continuous production of circles or ellipses superimposed upon a linear left- to-right progression movement. Compared to other cursive handwriting tasks in which the shape of letters often consists of different combinations of up and down strokes, loop writing can be regarded as a relatively

simple repetitive motor task. The loop-writing task was executed on a preprinted sheet of paper attached to a digitizer tablet. The loop-pattern height was 3, 6, 9 or 12 mm and the task was paced by an acoustic signal of 1, 2, or 3 Hz (see Fig. 1, chapter 1) of which the intensity changed sinusoidally across a clearly audible range. An experimental session consisted of twelve blocks of six repetitions of each amplitude-frequency combination, presented at random. Frequency-amplitude combinations did not differ within a block. The result was a total of 72 trials per session within a time span of 45 minutes.

In chapter 2 we look into the end-point variability of seven-year-old preparatory writers, while they executed the loop-writing task with amplitude *and* frequency set as spatial and temporal targets. Here the children were challenged to monitor their movements and correct errors while maintaining the movement production at the prescribed pace. Just having started learning to write, the children were generally efficient in changing a local parameter towards a goal parameter, while undershooting the amplitude requirements (except 3 mm). Amplitude errors were larger than frequency errors. However, they did not learn to reduce their errors over six repetitions. Preparatory writers are thus not yet able to learn over repetitions. From a maturational point of view younger and older first graders, differing in maturity based on birth date, executed loop writing quite differently; although the children as a group lagged behind the acoustic signal with their pen movement, younger first graders produced larger frequency errors, especially in "fast and small combinations", whilst the coordination variability between pen movement and acoustic signal was relatively low for older first graders.

In chapter 3 we explore the development of end-point variability over Grades 1, 2 and 3. Using the same loop-writing task, we demonstrate the complexity of the growing relationships between controlling movement amplitude and frequency as multiple, simultaneous task goals. Over the three years the children systematically produced smaller than instructed loop sizes, reflecting a general tendency to perform undershoots of spatial targets. Only the smallest amplitude (3 mm) was overshot at all ages. Developmentally, the children systematically improved in amplitude production with age. Of the instructed movement frequencies the children performed the 2-Hz most accurately, while 1-Hz was performed too fast and 3-Hz too slow. Developmentally, the children become more skilled in attaining the 3 Hz acoustically instructed frequency (error reduction of 33% over between 7 and 9 years of age). The children all showed a preference for the 6-mm amplitude and 2-Hz frequency. For the combined speed-amplitude instructions the children showed a growing sensitivity to the natural inverse relationships of the two parameters: at nine years of age larger amplitudes elicited lower frequencies and visa versa. We did not, however, find an increase in efficiency to correct errors but a decrease. The emphasis on spatial task goals in Dutch handwriting instruction manuals is at odds with the sensorimotor developmental processes, where children at the age of 9 are not yet fully able to correct performance errors.

In chapter 4, the final empirical study, we investigate the age-related changing abilities to meet the spatial and temporal task requirements of our loop-writing task using time series analysis. The goal here is to further explore the flexibility in handwriting performance and development, since the flexibility underlying handwriting performance gives, as an intrinsic property op development, a broader view on the underlying motor capacity. The capacity for sensorimotor synchronization and repetitive movement performance are captured by the standard deviation of the relative phase between pacing signal and handwriting movements and the capacity for self-similarity as expressed in time-lag dependent changes in autocorrelations of the digitized preparatory handwriting movements, respectively. The capacity for sensorimotor synchronization improves with age, while the time-dependent self-similarity shows that information of the recent past is highly relevant for the present and near future, indicating that writing a letter strongly influences the next letter, but not letters further on. Furthermore, this capacity hardly changes with age. These results indicate that flexible movement strategies already emerge early on in the first three years of formal handwriting education.

In sum, the three studies of part one of this thesis provide us with insights regarding age-related changes in end-point variability and structural variability of loop writing. Although end-point accuracy increases over the subsequent Grades (chapter 2 and 3) reflected by a decrease in variability, the structure of the variability, as reflected by (non)linear time-series analysis, increases markedly over the years, which is informative for the degree of adaptive capacity of the neuromotor system (chapter 4).

The explorative study of chapter 5 departs from a practical situation. In school settings, although motor performance is certainly an important factor during developing dysgraphia, more parameters influence the end product and should be taken into account. We therefore address the developing interaction between motoric, cognitive, and language processes. Next, we use these complex relationships between handwriting, motor and literacy skills to demonstrate the individual developmental route of two children compared to the mean and dispersion of performances of the group (chapter 6). In this study two children with dysgraphic handwriting with underlying differences in diagnosis were compared. Both explorative studies show that spelling and reading skills as well as motor skills are important parameters to be taken into account when assessing handwriting problems. Furthermore, the individual path of development is a factor that needs to be considered, while team consultations or interdisciplinary reflection and discussion (here described as counseling) are an essential part of helping children to fully develop their capacities.

Assessment and treatment decisions targeting primary school children who are developing their literacy skills need to be based on theoretical groundings, which we elaborate on in the introduction (chapter 1) and discussion (chapter 7). The capacity of therapists and teachers to make decisions concerning assessment, advise and remediation rests on the extent of their body of knowledge and skills. This thesis contributes to the body of knowledge of those who are committed to helping children re(gain) efficient handwriting.

Samenvatting

In dit proefschrift worden longitudinale studies gerapporteerd die de schrijfontwikkeling van een groep van 32 basisschool kinderen (leeftijd 7-9; groep 3 t/m 5) beschrijven. Het eerste deel van de these beschrijft drie empirische studies waarin de ontwikkelende efficiëntie in motorische controle wordt beschreven. Deze studies (hoofdstukken 2, 3 en 4) zijn gebaseerd op de analyse van gedigitaliseerde, voorbereidende schrijfbewegingen (x-y tablet) van herhalende lussen (zgn. guirlandes) die lijken op een serie van de letter *e*. In het tweede deel van dit proefschrift onderzoeken we de ontwikkeling van de relaties tussen karakteristieken van handschriftproducten (BHK overschrijftaak), kinematische variabelen van de motorische uitvoering van de lus-letters en de prestatieniveaus in lezen en spellen. De taalvaardigheid scores zijn afkomstig uit het bestaande leerling-volg systeem van de basisschool (hoofdstuk 5). Tot slot worden deze metingen gebruikt in een dubbele 'case' studie, waarin twee kinderen worden beschreven, die beiden een dysgrafisch schrijfontwikkeling lieten zien maar verschillend werden begeleid, op basis van verschillende uitkomsten tijdens het onderzoek van de motorische- en taalcapaciteit en een verschil in 'constraints' naar aanleiding van de gestelde diagnosen. De variabiliteit op individueel niveau wordt vergeleken met het gemiddelde van de gehele groep en beschreven vanuit een interdisciplinair perspectief (hoofdstuk 6).

Voor de empirische studies over de ontwikkeling van motorische efficiëntie hebben wij een cyclische, niet taal-gerelateerde schrijftaak ontwikkeld, teneinde de motorische en cognitieve ontwikkeling op een kinematisch niveau te kunnen onderzoeken. Hierbij werd een lus-letter die lijkt op de letter *e* gebruikt. In essentie is dit een schrijftaak die zo is samengesteld dat herhaalde productie van ellipsen die geprojecteerd wordt op een lineaire, d.w.z. met constante snelheid van links-naar-rechts gaande beweging. Vergeleken met cursief schrift waarbij de letters bestaan uit verschillende combinaties van opgaande en neergaande pen bewegingen, kan de lus-letter e gezien worden als een relatief eenvoudige, zich herhalende motorische taak.

De lus-letters worden met een elektronische pen geschreven op een voorgedrukt A4 papier, dat op een x-y tablet werd gelegd. De hoogte van het lus-letterpatroon was 3, 6, 9 of 12 mm, waarbij het tempo van de uitvoering door een akoestisch signaal (1, 2 en 3 Hz) met sinusoïdaal variërende intensiteit werd geïnstrueerd. Het experiment bestond uit 12 blokken van 6 herhalingen van iedere amplitude en frequentie combinatie, die in willekeurig volgorde werden aangeboden. De amplitude-frequentie combinaties werden binnen een blok niet gevarieerd. De kinderen maken ieder jaar in maart 72 trials per sessie, met een tijdsduur van 45 minuten.

In hoofdstuk 2 wordt de uitvoering op het niveau van de pen beweging (eindpunt variabiliteit) van 7-jarige kinderen beschreven, terwijl zij de cyclische schrijfbeweging uitvoeren met zowel amplitude als frequentie doelen. De kinderen moeten hun bewegingen controleren en de fouten corrigeren terwijl zij aan de spatiële en temporele taakeisen van de opdracht proberen te voldoen. Over het algemeen genomen zijn de kinderen, die net hebben leren schrijven, in staat de uitvoering aan te passen aan het doel, waarbij zij systematisch de 6, 9 en 12 mm amplitude niet haalden en zij boven de 3 mm hoogte uitschoten. De fouten in uitvoering van de amplitude zijn groter dan de fouten in de frequentie. Er blijkt geen leermoment aanwezig te zijn bij 6 herhalingen van de taak. Vanuit het gezichtspunt van rijping verschillen jongere en oudere leerlingen (geselecteerd op geboortedatum) binnen de groep. Hoewel groep 3 als geheel het akoestisch signaal niet kan bijhouden met de penbewegingen, maken jongere leerlingen, geselecteerd op geboortedatum, grotere fouten m.b.t. de frequentie eisen, met name bij de “snelle en kleine combinaties” (3 mm, 3 Hz) en laten de oudere leerlingen een relatief kleine spreiding in de variabiliteit van de coördinatie zien.

In hoofdstuk 3 wordt de ontwikkeling van de variabiliteit van de eindbeweging tussen groep 3 en groep 5 bekeken. Gebruik makend van dezelfde lus-letter taak belichten wij de complexiteit van de veranderende relaties tussen het beheersen van de amplitude en frequentie taakeisen. Over de drie jaar genomen worden de voorgeschreven amplitudes systematisch niet gehaald, wat duidt op de algemene tendens om binnen ruimtelijke doelen te blijven. In de drie jaar van het onderzoek blijken de kinderen beter in staat tot het uitvoeren van de amplitude eisen. Op alle leeftijden echter wordt de 3-mm amplitude systematisch voorbijgeschoten. De 2-Hz frequentie wordt het meest nauwkeurig uitgevoerd, de 1 Hz ging te langzaam, de 3 Hz te snel. Gedurende de drie jaar verminderen de frequentiefouten echter met 33% voor de 3 Hz. De kinderen hebben een voorkeur voor de combinatie van 6 mm

amplitude en de 2-Hz frequentie taak eis. De kinderen laten in deze periode van drie jaar een groeiende gevoeligheid voor de natuurlijke inverse relatie tussen snelheid en nauwkeurigheid zien. Op 9-jarige leeftijd lokken grotere amplitude lagere frequenties uit en kleinere amplituden hogere frequenties. De kinderen worden echter niet efficiënter in het corrigeren van fouten: zij worden minder efficiënt. De nadruk die in de Nederlandse handschriftmethoden gelegd wordt op het schrijven tussen steeds smaller wordende lijnen, staat op gespannen voet met de sensomotorische ontwikkeling: kinderen in groep 5, 9 jaar oud, zijn nog niet volledig is staat de fouten in uitvoering bij te stellen.

De laatste empirische studie (hoofdstuk 4) beschrijft, met behulp van tijdseries analysen, de aanpassingen aan taakeisen van de lus-letter taak. Het doel van deze studie is een verdere exploratie van de flexibiliteit in handschriftproductie en -ontwikkeling. Flexibiliteit is een eigenschap van het zich ontwikkelende neuro-motorisch systeem dat het uitvoeren van steeds wisselende motorische taken mogelijk maakt en een bredere kijk geeft op de onderliggende motorische capaciteit. Het vermogen tot sensori-motorische synchronisatie o.a. uitgedrukt middels de standaard deviatie van de relatieve fase tussen het akoestisch signaal en de handschriftbewegingen wordt geanalyseerd, terwijl het vermogen tot zelfherhaling onderzocht wordt door autocorrelaties van de cyclische schrijfbewegingen in verschillende tijdsintervallen. Het vermogen tot sensori-motorische synchronisatie verbetert gedurende drie jaar schrijfonderwijs, terwijl de analyse van het vermogen tot zelfherhaling laat zien dat voor de onderzochte kinderen informatie uit het recente verleden van hun schrijfbewegingen relevant is voor het nu en de nabije toekomst, dat wil zeggen dat het schrijven van een letter de volgende letter beïnvloedt, maar dat letters verderop in de tekst hierdoor niet beïnvloed zijn. Het vermogen hiervoor veranderd nauwelijks tijdens het ouder worden. Deze resultaten laten zien dat flexibele bewegingsstrategieën vroeg in de eerste drie jaar van het handschriftonderricht gevormd worden.

Samengevat geven de drie studies uit eerste deel van dit proefschrift ons inzicht in de verschillen tussen eindpuntvariabiliteit en structurele variabiliteit. De eindpunt nauwkeurigheid neemt toe naarmate de kinderen ouder worden, waarbij de eindpuntvariabiliteit dus verminderd. De veranderingen in de structuur van de variabiliteit, zoals beschreven middels (non)lineaire time-series analysen, laten duidelijk zien dat deze structurele variabiliteit vergroot naarmate de kinderen ouder worden en meer training in de schrijfvaardigheid hebben gehad. Dit geeft ons informatie over het adaptief vermogen van het neuro-motorisch systeem.

De exploratieve studies die gerapporteerd worden in hoofdstuk 5 en 6 vertrekken vanuit een praktisch oogpunt. Bij het beoordelen van het handschrift in de dagelijkse praktijk zijn meer factoren dan de motorische uitvoering van belang voor besluitvorming over een kind met een atypische handschrift ontwikkeling. Daarom hebben wij de ontwikkelende interacties tussen motorische, cognitieve en taalprocessen als onderwerp van dit onderzoek gekozen (hoofdstuk 5). De complexe relaties tussen handschrift, motorische- en taalontwikkeling zijn vervolgens gebruikt om de individuele ontwikkelingen van twee kinderen af te zetten tegen het gemiddelde en de spreiding van de prestaties in de gehele groep (hoofdstuk 6). In deze studie volgen wij de ontwikkeling van twee kinderen met een dysgrafisch handschrift waarbij verschillende onderliggende diagnosen een rol speelden. Beide exploratieve studies laten zien dat zowel spellings- en leesvaardigheid als motorische vaardigheden belangrijke parameters zijn die meegewogen dienen te worden wanneer problemen in de ontwikkeling van het handschrift worden beoordeeld. Bovendien is de individuele ontwikkeling een factor die meegenomen moet worden, terwijl teamoverleg of interdisciplinair spiegelen en discussie (hier geduid als 'counseling') een essentieel onderdeel vormen bij het helpen van kinderen hun vermogen zo volledig mogelijk te laten benutten.

Beslissingen bij onderzoek, begeleiding en behandeling moeten gebaseerd zijn op theoretische overwegingen, die wij uitgewerkt hebben in de introductie (hoofdstuk 1) en de discussie (hoofdstuk 7). Het vermogen om keuzen te maken tijdens onderzoek, advisering en begeleiding of behandeling van individuele kinderen is afhankelijk van de mate van kennis en vaardigheden aanwezig bij therapeuten of leerkrachten. Dit proefschrift draagt bij aan die basis (of zgn. 'body of knowledge') van diegenen die zich inzetten om kinderen te helpen om een leesbaar handschrift met voldoende snelheid te ontwikkelen.

Dankwoord

Now this is the Law of the Jungle, as old and as true as the sky
And the Wolff that shall keep it may prosper, but the Wolff that shall break it must die
As the Creeper that girdles the tree-trunk the Law runneth forward and back –
For the strength of the Pack is the Wolff, and the strength of the Wolff is the pack.[1]

Vele mensen hebben mij meegenomen op hun weg, teveel om allen te noemen. Aan de wieg heeft mijn moeder Dr. J. G Stork-Penning gestaan, aan wiens filosofische discours ik veel te danken heb. Ook was daar mijn vader, die alles, een leven lang, gefaciliteerd heeft.

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Mijn promotor, Prof. dr Ruud Meulenbroek is van onschatbare waarde

1 *The Law for the Wolves by Rudyard Kipling: Second Jungle Book*

geweest. Zijn gesprekken en aansturing zijn onmisbaar geweest bij mijn eerste stappen op wetenschappelijk gebied. Dank voor je geduld en al je inspanningen. Ook de gezellige etentjes met Hanneke zijn onvergetelijk, het was mij een genoegen jullie te hebben kunnen meemaken. Mijn co-promotor Dr. Jules Ellis heeft zijn gewicht (goud waard) in de strijd gegooid op het moment dat statistiek mij dreigde te overspoelen. Zijn wijze les dat je niet meer moet willen bewijzen dan de resultaten laten zien, zal ik niet vergeten. Dank voor je inzet, je nauwgezette controles en tijdsinvestering. Voor Prof. dr Anna Bosman, de voorzitter van de manuscript commissie heb bijzondere waardering. Ik ben onder de indruk van de wijze waarop zij naar mijn proefschrift heeft gekeken. Het komt niet vaak voor dat inhoudelijke opmerkingen bij mij vragen naar boven brengen die mij forceren tot nadenken en mij op geheel andere wijze naar het onderwijs hebben doen kijken. Mijn dank hiervoor.

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Het deelnemen aan de projectgroep ter ontwikkelen van het Evidence Statement 'Motorische schrijfproblemen bij kinderen' is de trigger geweest om tenslotte toch de beslissing te nemen onderzoek te gaan doen op het gebied van handschriftontwikkeling. Anneloes, Ingrid, Ria, Bouwien, Bert en Mathieu, het was mij een genoegen, jammer dat de meningsverschillen niet verder uitgewerkt kunnen worden.

De conferenties van de International Graphonomic Society, de IGS, brengen wetenschappers uit vele landen met belangstelling voor handschrift in de ruimste zin van het woord bij elkaar. Niet alleen leer je de wereld kennen (Amerika, Japan, Australië), maar ook zijn de contacten van grote waarde. A special word of thanks for Prof. Anna Barnett of Oxford Brookes University for giving me the opportunity to visit Oxford Brookes, her help in formulating my research and the invitation to join her, Annabel Molyneaux, Melissa Prunty and Emma Sumner for a mini symposium at the Writing conference in Amsterdam.

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Jurjen, wij gingen samen naar de master Research in Cognitive Neurscience en zijn vervolgens een nieuwe wereld, die van 'motor control' ingestapt. Zie waar we uitgekomen zijn. Volledig ongeschikt om binnen de fysiotherapie te *functioneren*, laat staan tot activiteiten en participatie te komen. Je gedrevenheid houdt mij wakker en je diepgaande kennis op het terrein van action science heeft mij ook aangezet tot het verbreden van mijn kijk op het leven. Hoewel je niets weet van handschriftontwikkeling is je bijdrage aan mijn onderzoek onmisbaar gebleken. Laten wij nog een poosje doorgaan in deze wetenschappelijke kosmos, het bevalt mij best.

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Curriculum Vitae

Ida Stork werd op 3 september 1948 geboren in Den Haag. Na het behalen van het eindexamen M.M.S. aan het Dalton Lyceum te Voorburg, bezocht zij een half jaar de International School in Den Haag, gevolgd door een half jaar studie aan de Universiteit van British Columbia in Vancouver, Canada. Na twee jaar werkzaam te zijn geweest op de operatiekamer neurochirurgie van de Valeriuskliniek in Amsterdam, startte zij haar opleiding Fysiotherapie aan de S.A.F.A. te Amsterdam. Na een reeks vakinhoudelijke cursussen (o.a Nederlandse Opleidingen NDT (1977), Specialisatie Psychomotoriek bij kinderen (1982), Kinderfysiotherapie en Ontwikkelingsstoornissen bij Kinderen van 0-2 jaar (1983) en Therapie nach Vojta (1987)) volgde in 1989 een registratie als Kinderfysiotherapeut. In 1995 nam zij deel aan de cursus scholing in Wetenschap I-III van de Stichting Wetenschap en Scholing Fysiotherpie. In 2003 behaalde zij haar Master of Research in Cognitive Neuromotor Science aan het (toemalig) Nijmeegs Instituut voor Cognitie en Informatieverwerking (NICI) van het Academisch Centrum Sociale Wetenschappen Katholieke Universiteit Nijmegen.

Vanaf 1975 was zij werkzaam op de kinderafdeling van achtereenvolgens het revalidatiecentrum "De Trappenberg", het Diaconessenhuis te Utrecht en op de afdeling kinderneurologie van het Academisch Ziekenhuis te Utrecht. In 1983 startte zij een praktijk Kinderfysiotherapie in Doorn, waar zij tot 2000 werkzaam was. Sinds 2000 is zij zelfstandig werkzaam in Woudenberg, waar zij sinds 2013 verbonden is aan het Expertisecentrum Uniek, in een samenwerkingsverband met scholen.

Van 1981-2002 was zij redactielid van Stimulus, tijdschrift voor geselecteerde vakliteratuur voor de fysiotherapeut en kinesitherapeut van Bohn, Scheltema & Holkema.

Van 1985 - 2013 was zij als praktijkdocent verbonden aan de opleiding Kinderfysiotherapie, sinds 2005 als hogeschooldocent aan de Opleiding Master Fysiotherapie afstudeerrichting Kinderfysiotherapie van de Hogeschool Utrecht, tevens vanaf 2002 docent nascholing voor de schrijfcursus van de Hogeschool Utrecht.